



Global cosmological signal detection experiments at radio frequencies

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Symposium on Women in Physics
Networking, Innovation, Opportunity, and Equity

11 - 12 SEPTEMBER, 2026

CMB DISTORTION LAB, RRI

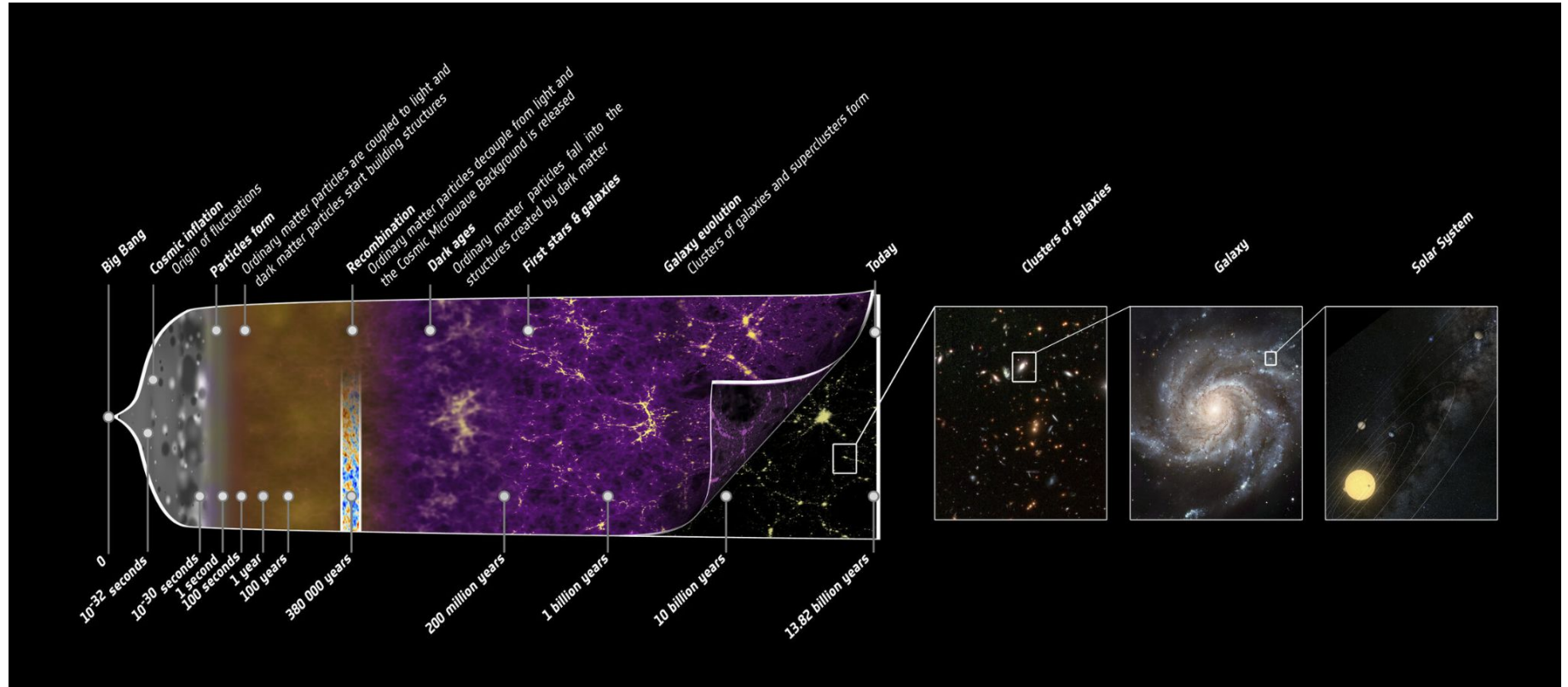
11/24 ~ 46%



+ Collaborators, Staff at Electronics and Mechanical Engineering Services,
Gauribidanur field station, Visiting project students

THANKS - FUNDING AGENCIES - DST, SERB-CRG, ISRO

Cosmic timeline

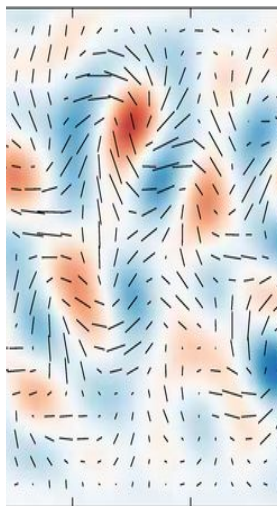


Courtesy : ESA

B
I
G

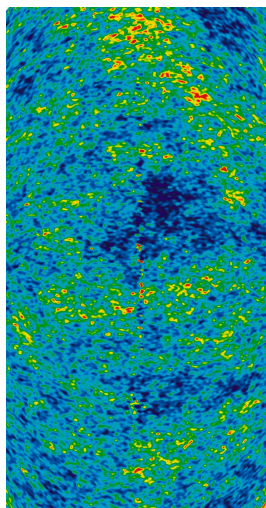
B
A
N
G

t_0



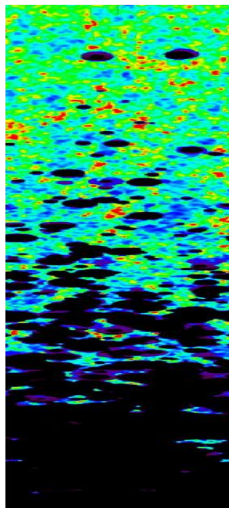
INFLATION

$t=1e-25$ s



RECOMBINATION

$t=380000$ y



COSMIC DAWN
REIONIZATION

$t=300e6$ y

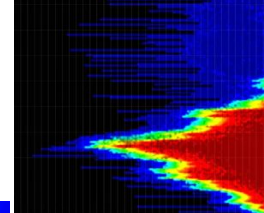


OBSERVER

$t= 13.8e9$ y

MSR ++ (ApJ 2015)
Sathish, K., MSR,
Sarkar, (AJ, 2024)

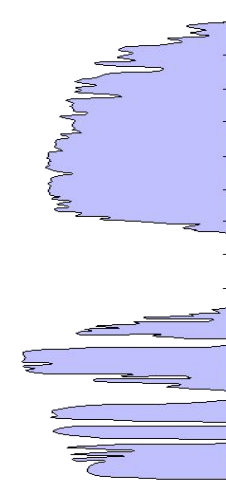
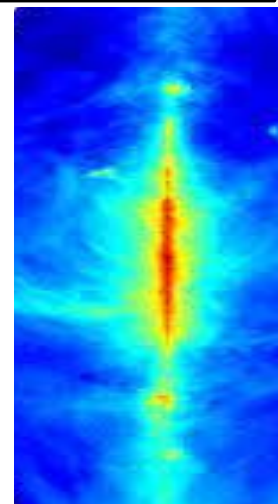
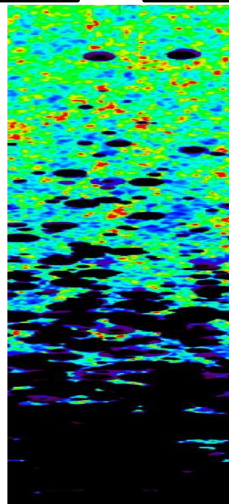
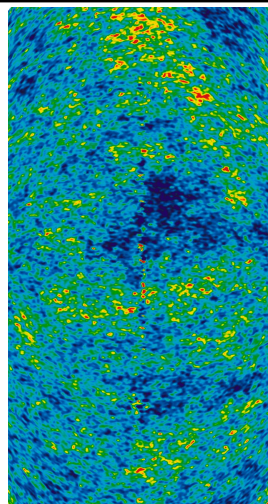
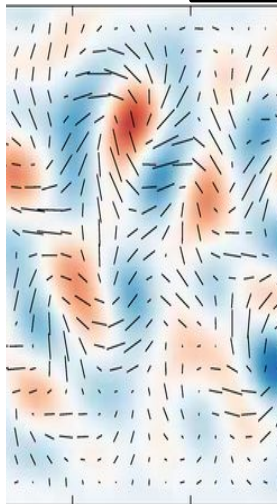
MSR ++ (AJ 2017)
Hensley,..MSR++
(ApJ 2022)



B
I
G

B
A
N
G

t0



INFLATION

RECOMBINATION

COSMIC DAWN
REIONIZATION

GALACTIC
EMISSION

ATMOSPHERE
INTERFERENCE

OBSERVER

t=1e-25 s

t=380000 y

t=300e6 y

t= 13.8e9 y

t= 13.8e9 y

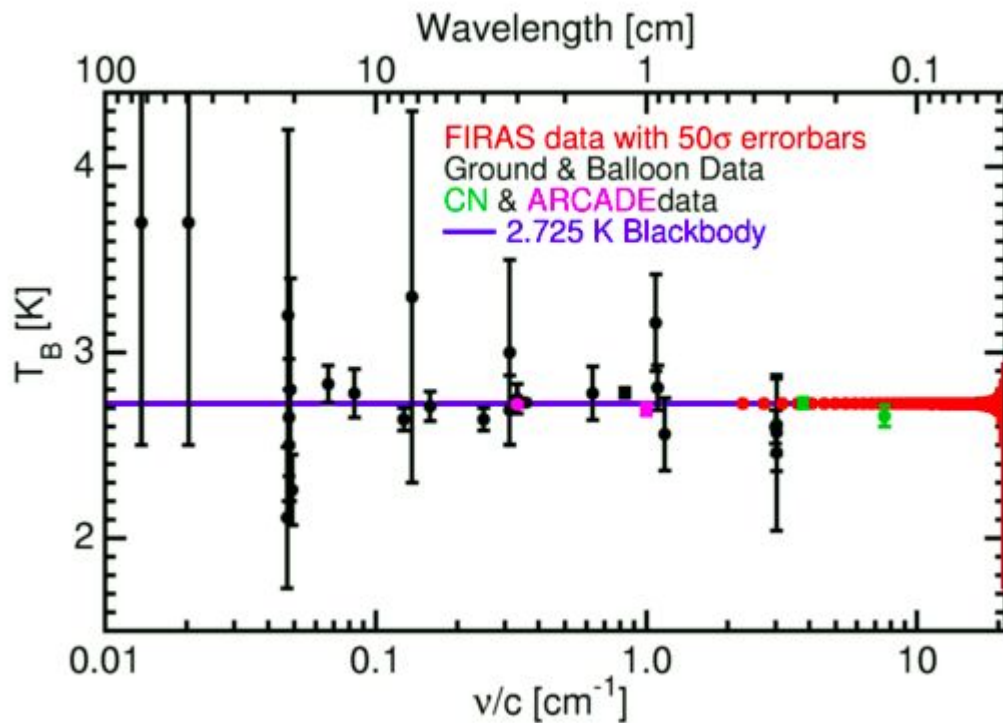
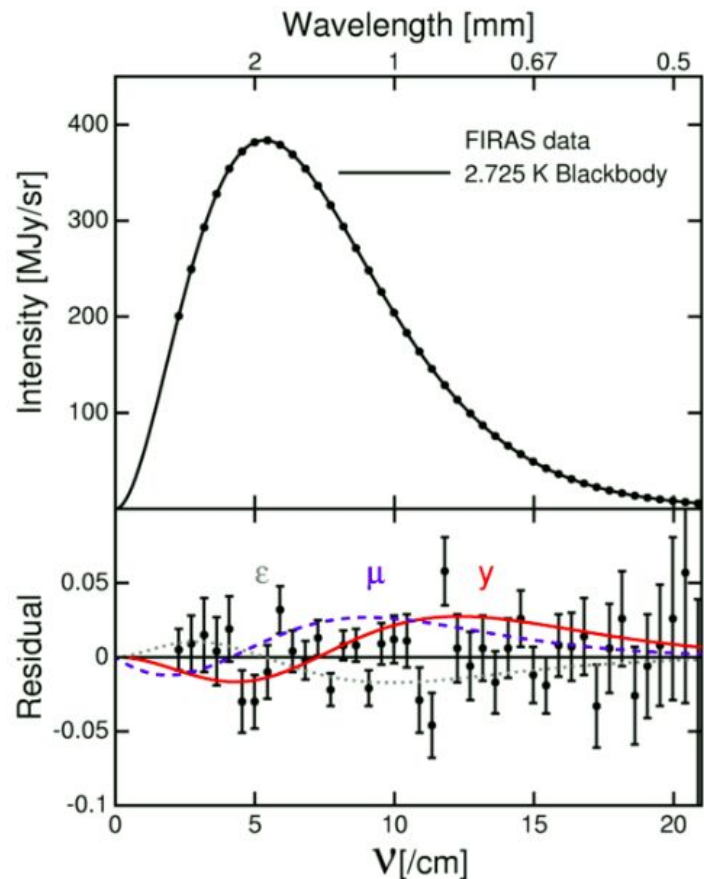
t= 13.8e9 y

MSR++ (JLTP 2019)
SO collaboration
(JCAP 2019)

MSR++ (ApJ 2017)
MSR++ (ExA 2023)

1.Ghosh, MSR, S.Singh
(2023)
2.T.Singh, MSR (In prep)

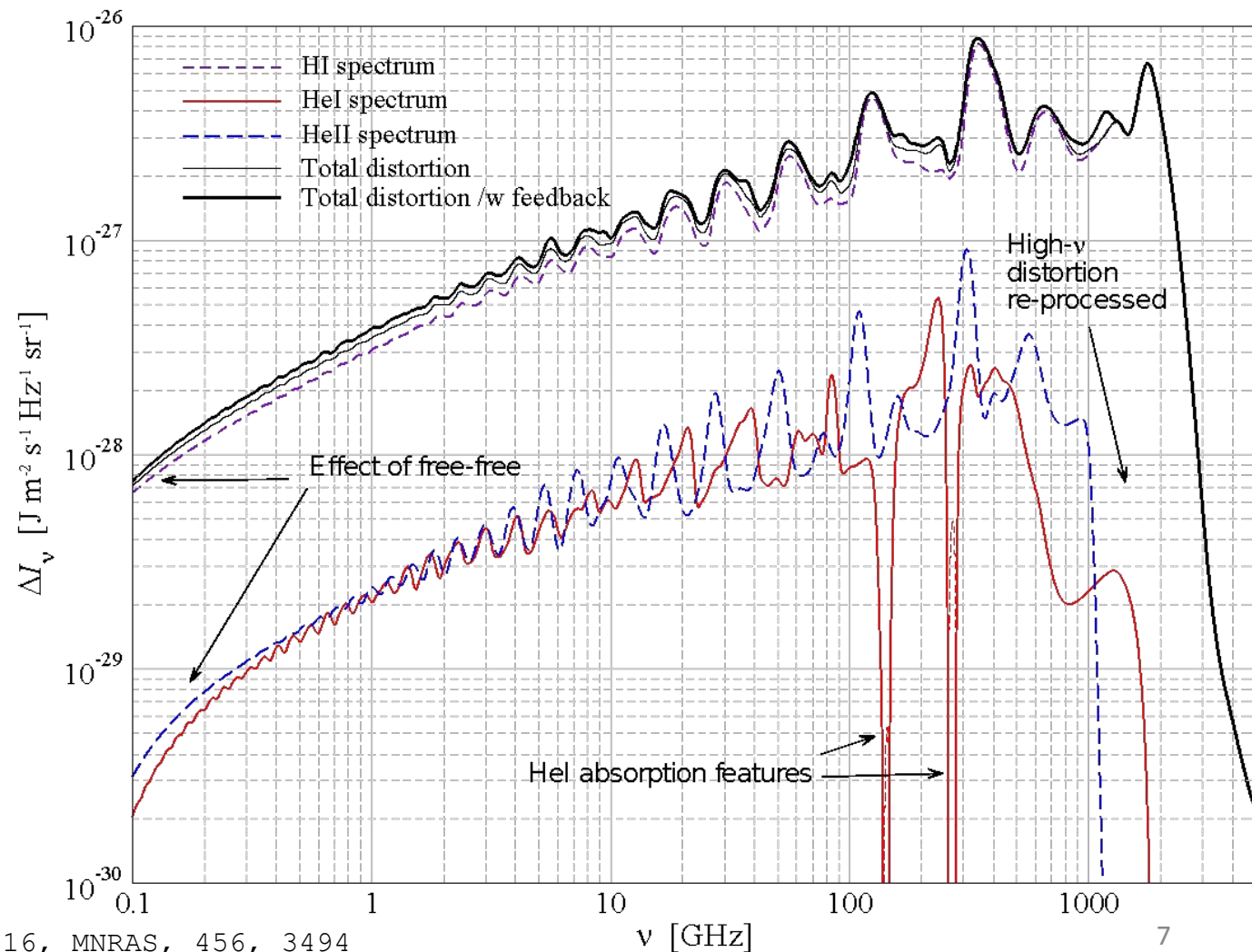
Quick note on CMB spectrum



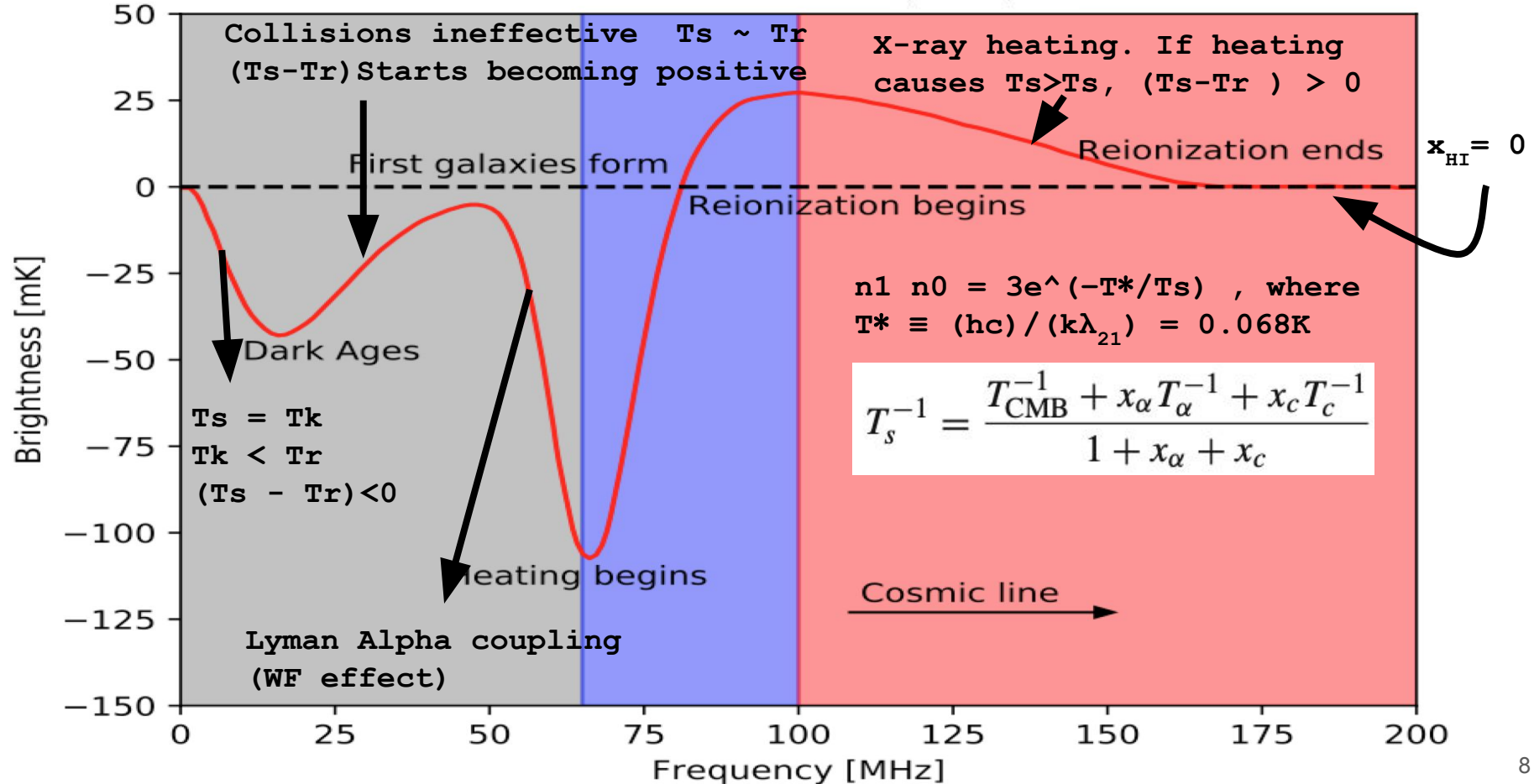
Courtesy : <https://www.astro.ucla.edu/~wright/CMB.html>

$500 < z < 2000$
 for hydrogen,
 $1600 < z < 3500$
 for He II $\rightarrow$ He I
 and $5000 < z < 8000$
 for He III
 $\rightarrow$ He II
 recombination

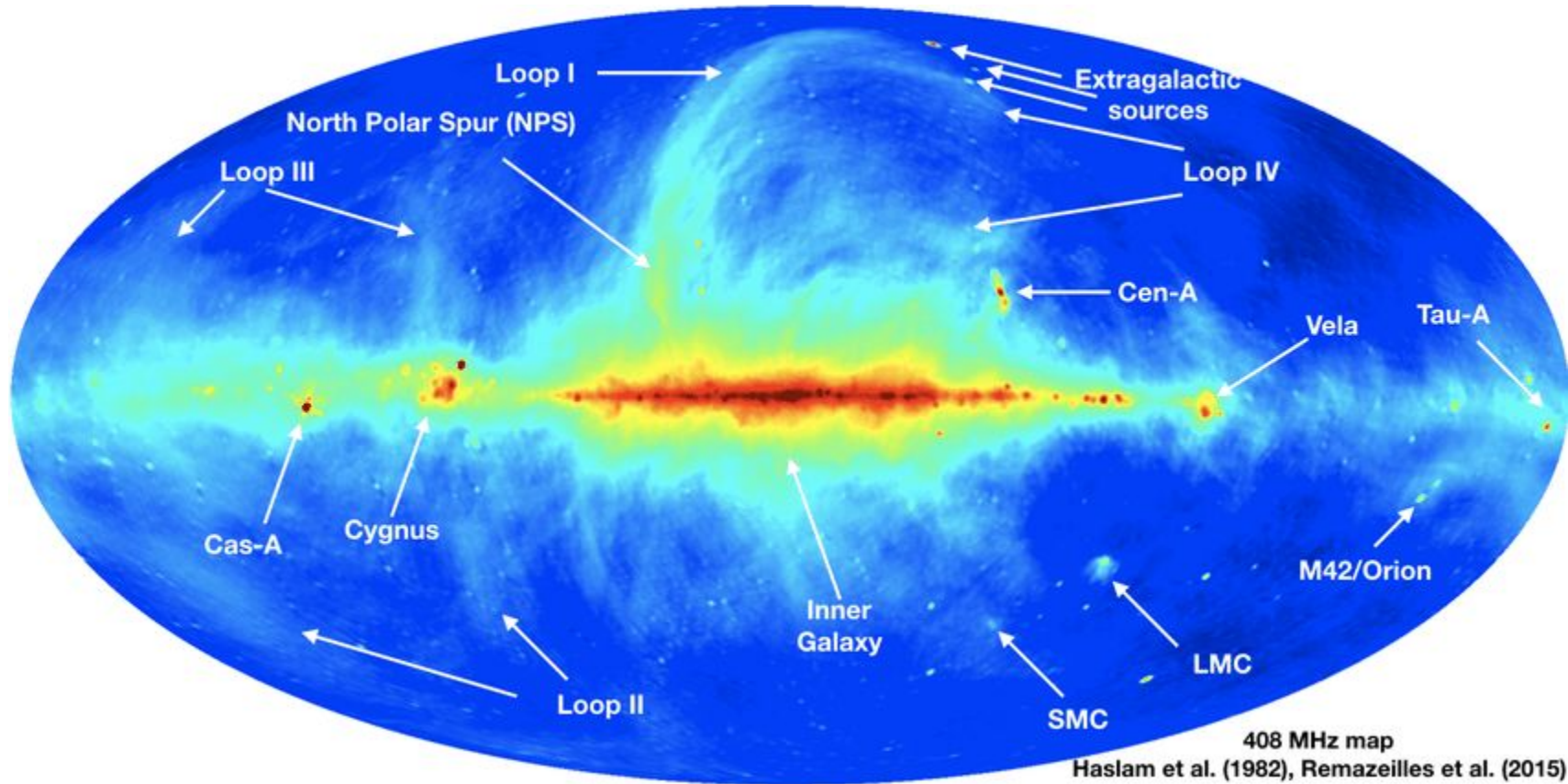
Free-bound, and
 bound-bound
 transitions emit
 photons that are
 additive
 distortions to
 the CMB spectrum



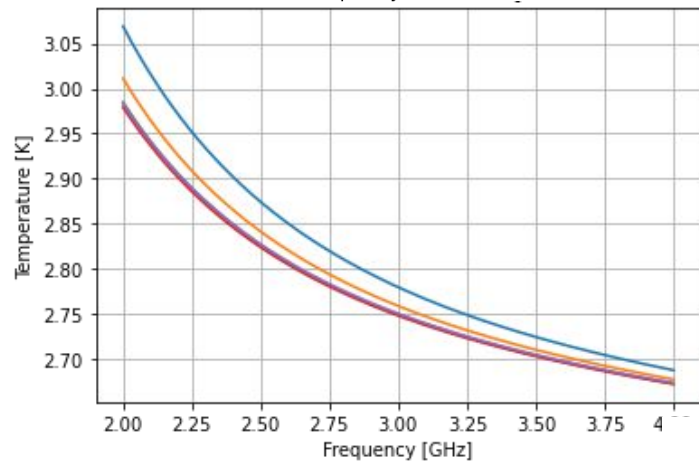
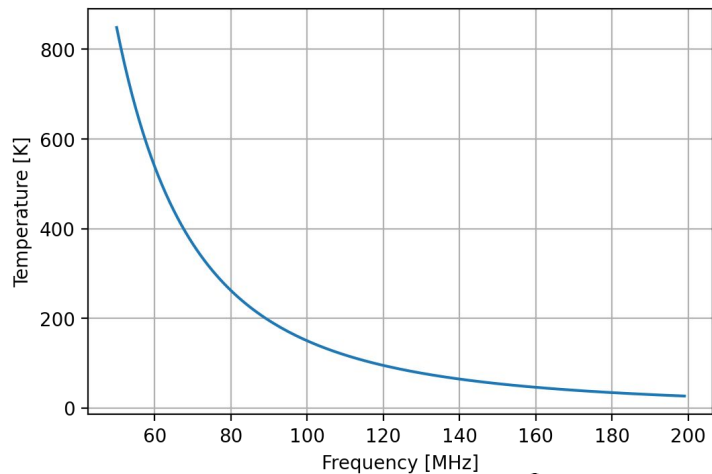
$$\delta T_b^{\text{obs}}(\nu) \approx 27 x_{\text{HI}} \left(\frac{\Omega_b h^2}{0.022} \right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10} \right)^{\frac{1}{2}} \left(\frac{T_s - T_R}{T_s} \right) \text{mK}.$$



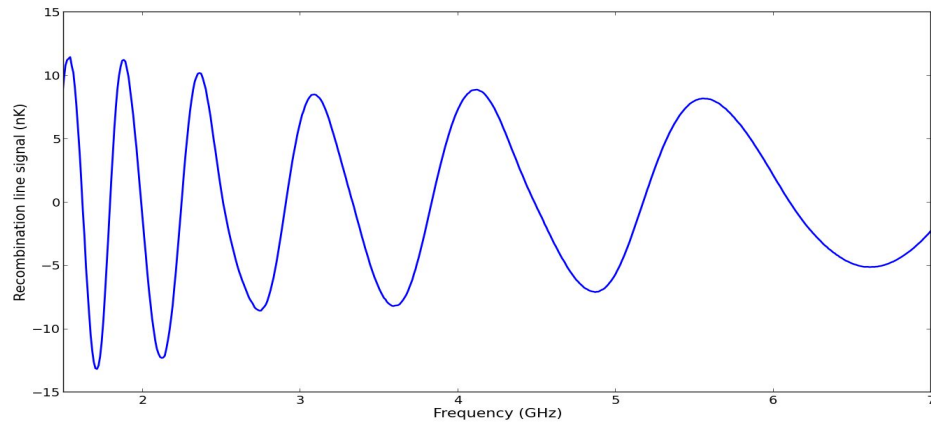
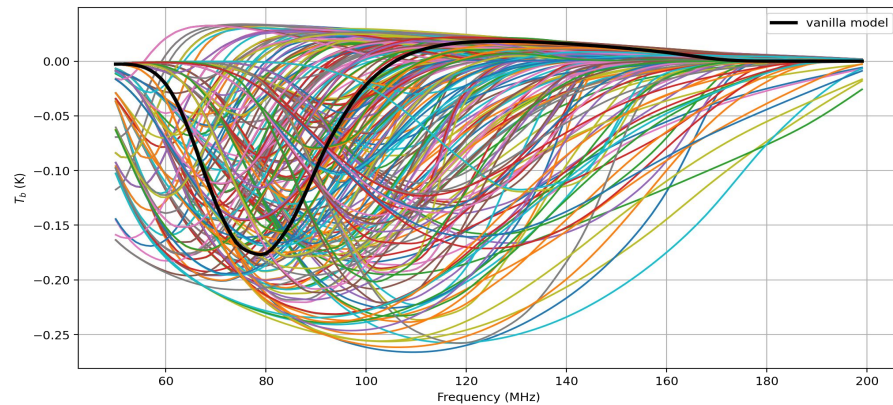
WHAT IS IT THAT WE ARE LOOKING THROUGH??



BACKGROUND

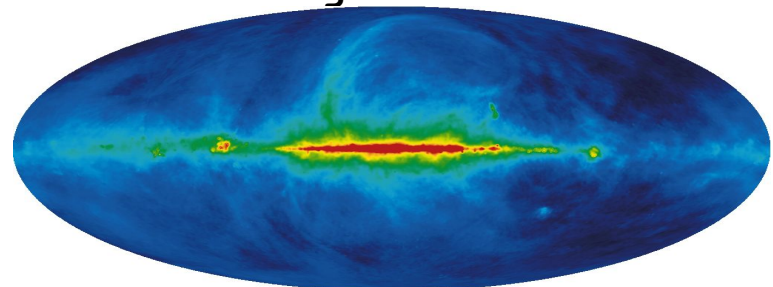


SIGNAL



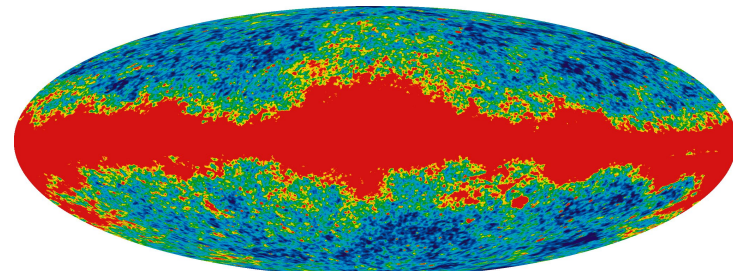
GMOSS : Global Model for the Radio Sky Spectrum

- We don't understand foregrounds well
- We need to separate foregrounds without removing the UNKNOWN signal!
- We have - data
 - All sky maps 22 MHz, 45 MHz
 - 150 MHz, 408 MHz, 1420 MHz, 23 GHz
- Physics
 - Galactic synchrotron
 - Possible break
 - Different source populations
 - Free free emission
 - Absorption



408 MHz

Haslam et.al



23 GHz

WMAP science team 11

Modeling

CD / EoR

Model 1:

$$T(\nu) = C \left(\nu^{-2} (\gamma^{2\alpha_1 - 3} \int_{x(\gamma_{min})}^{x(\gamma_{max})} F(x) x^{-\frac{p_1 - 3}{2}} dx + \gamma^{2\alpha_2 - 3} \int_{x(\gamma_{min})}^{x(\gamma_{max})} F(x) x^{-\frac{p_2 - 3}{2}} dx + T_x \nu^{-2.1} \right) e^{-\left(\frac{\nu t}{\nu}\right)^{2.1}} + T_e (1 - e^{-\left(\frac{\nu t}{\nu}\right)^{2.1}})$$

Diagram annotations for Model 1:

- Diffuse warm ionized gas** (points to the integrals)
- Emission** (points to the T_e term)
- Absorption** (points to the exponential cutoff term)
- Synchrotron steepening** (points to the γ terms in the integrals)
- Normalization** (points to the C factor)

Model 2:

$$T(\nu) = C1 \left(\nu^{-\alpha_1} + \frac{C_2}{C_1} \nu^{-\alpha_2} + T_x \nu^{-2.1} \right) e^{-\left(\frac{\nu t}{\nu}\right)^{2.1}} + T_e (1 - e^{-\left(\frac{\nu t}{\nu}\right)^{2.1}})$$

Diagram annotations for Model 2:

- Diffuse warm ionized gas** (points to the $\nu^{-\alpha_2}$ term)
- Absorption** (points to the exponential cutoff term)
- Emission** (points to the T_e term)
- Normalization** (points to the $C1$ factor)
- Different source populations** (points to the $\nu^{-\alpha_1}$ and $\nu^{-\alpha_2}$ terms)

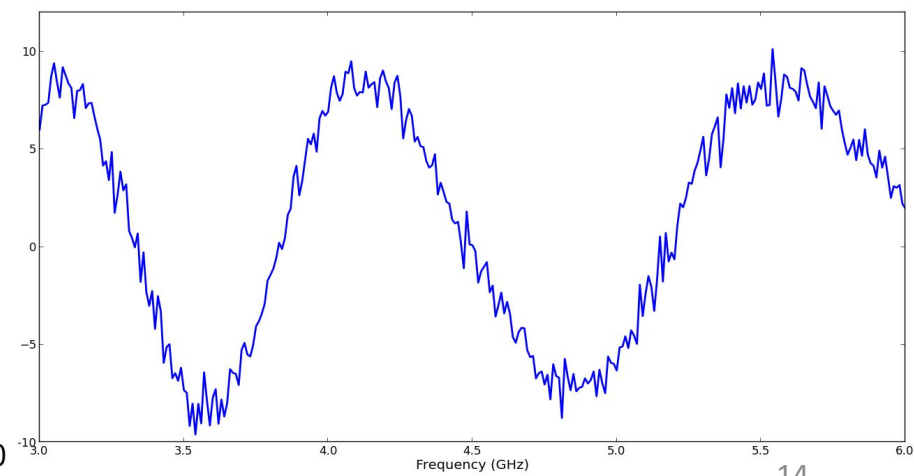
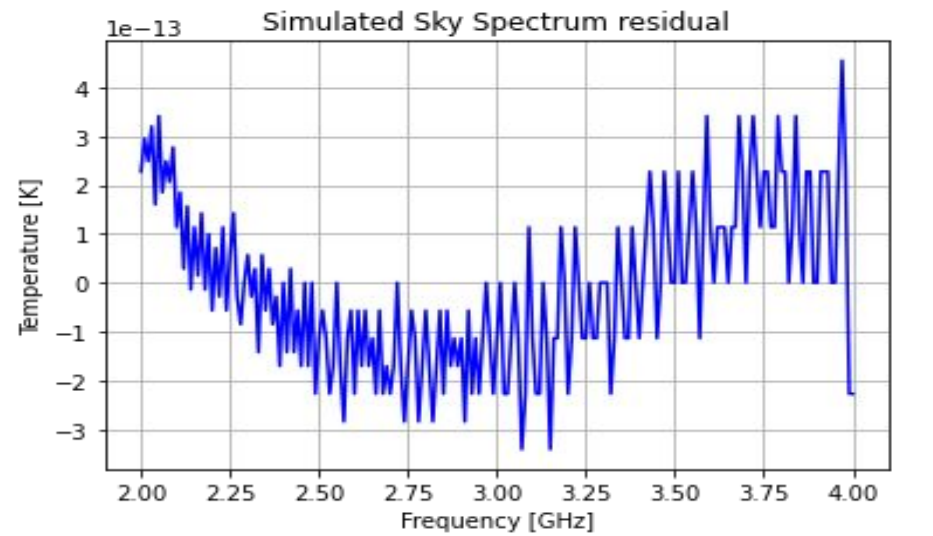
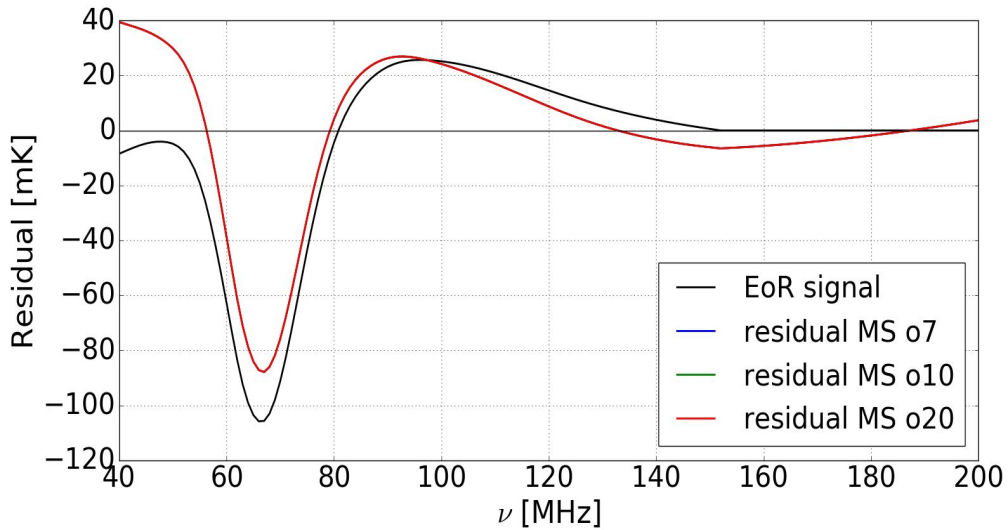
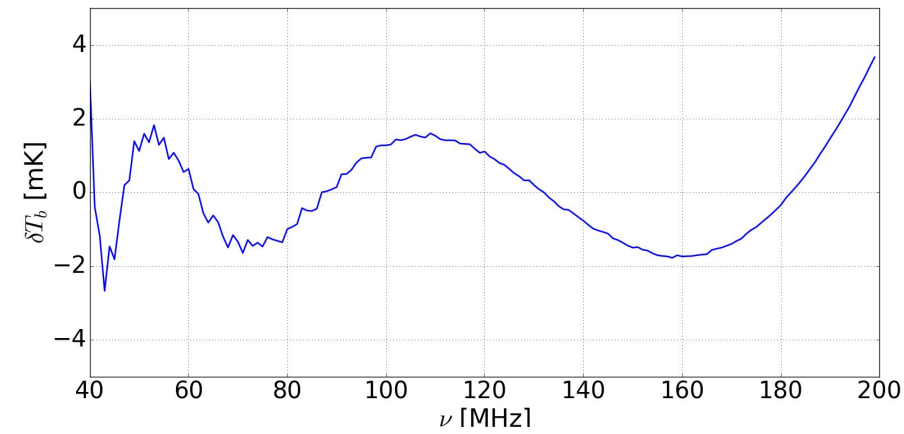
Mathematical methods for signal detection

- Devise a class of **Maximally Smooth** functions
- Polynomial in $\log(\nu)$ and $\log(T)$ space

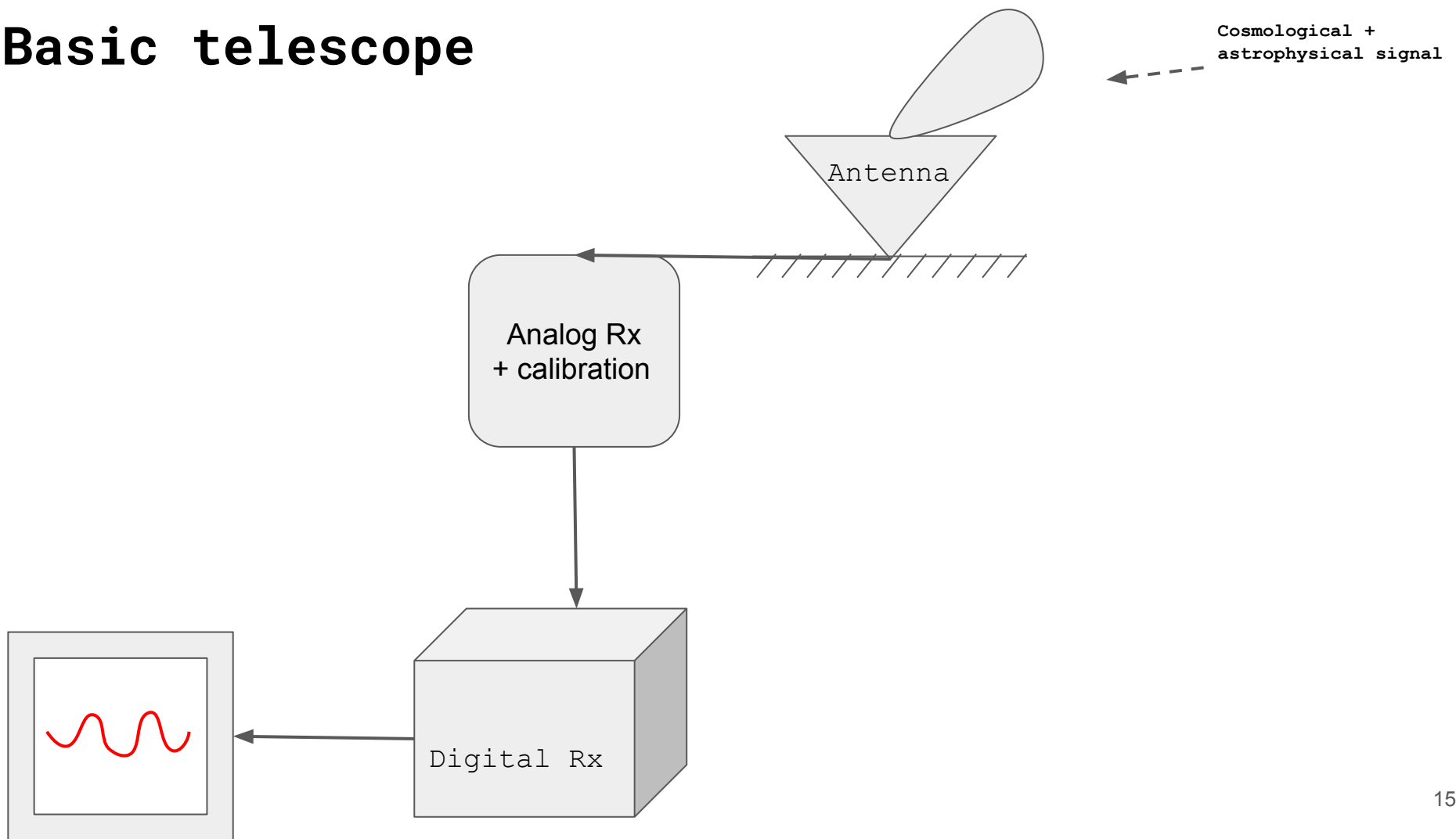
$$10^{\sum p[i] * \log(\nu/\nu_0)^i}$$

- Taylor expansion about lowest freq. ν_0 in band
- Do not allow zero crossings in higher order derivatives
- Over larger (frequency independent) beam averaged scales – foregrounds are smooth, Galactic plane best avoided

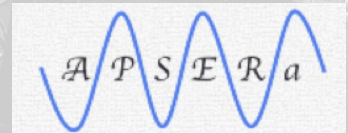
Foreground subtraction



Basic telescope



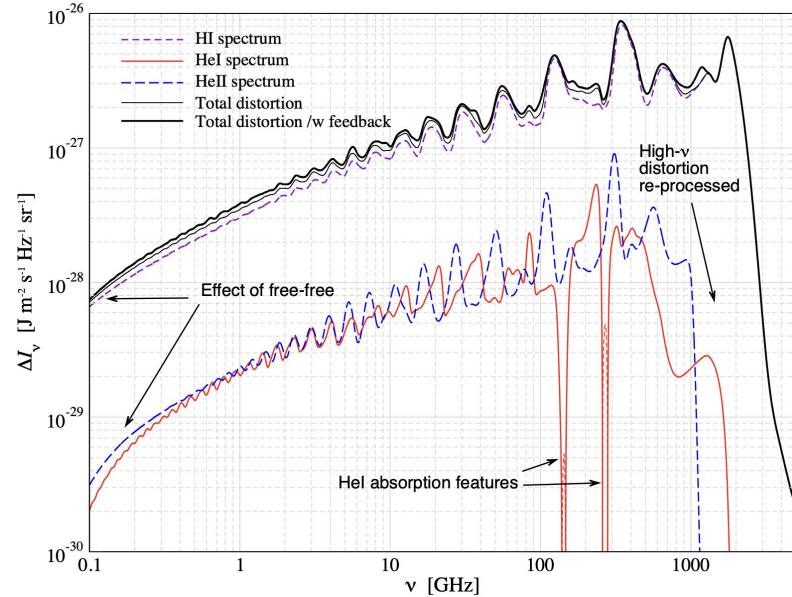
APSERa - an upcoming S-band cosmology experiment



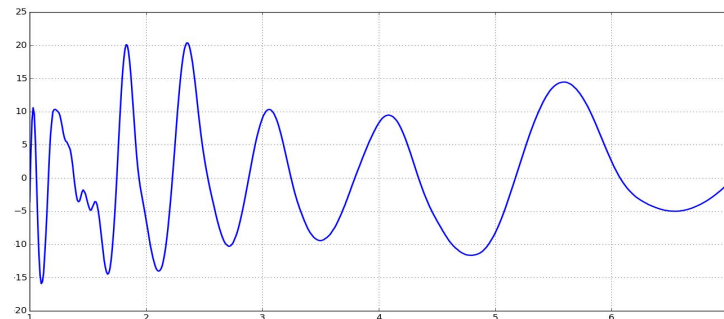
Additive Spectral Distortions from Epoch of Recombination

Hydrogen recombination lines from redshift ~ 1100 s

- Atoms formed as universe expanded and cooled.
- Electron can recombine directly to the ground state (optically thick channel), or to any of the higher excited states, and eventually trickle down the levels and reach the ground state (free-bound transition).
- Photons in the very distant Wein tail of CMB blackbody spectrum can keep hydrogen ionised till a photon temperature of $T_p = 0.26$ eV (hence no H recombination at $T_p \sim 13.6$ eV).
 - Recombination signal goes from 100 MHz $\sim$ THz
 - GHz: Peak-Peak amplitude ~ 10 s nK
 - Global Signal (with small anisotropies)
 - Unpolarized
- Why? - Confirmation of thermal, ionization history of the Universe, independent measure of cosmological parameters, experimental measurement of prestellar Helium abundance.
- Requires a receiver sensitivity of 1 part per billion!

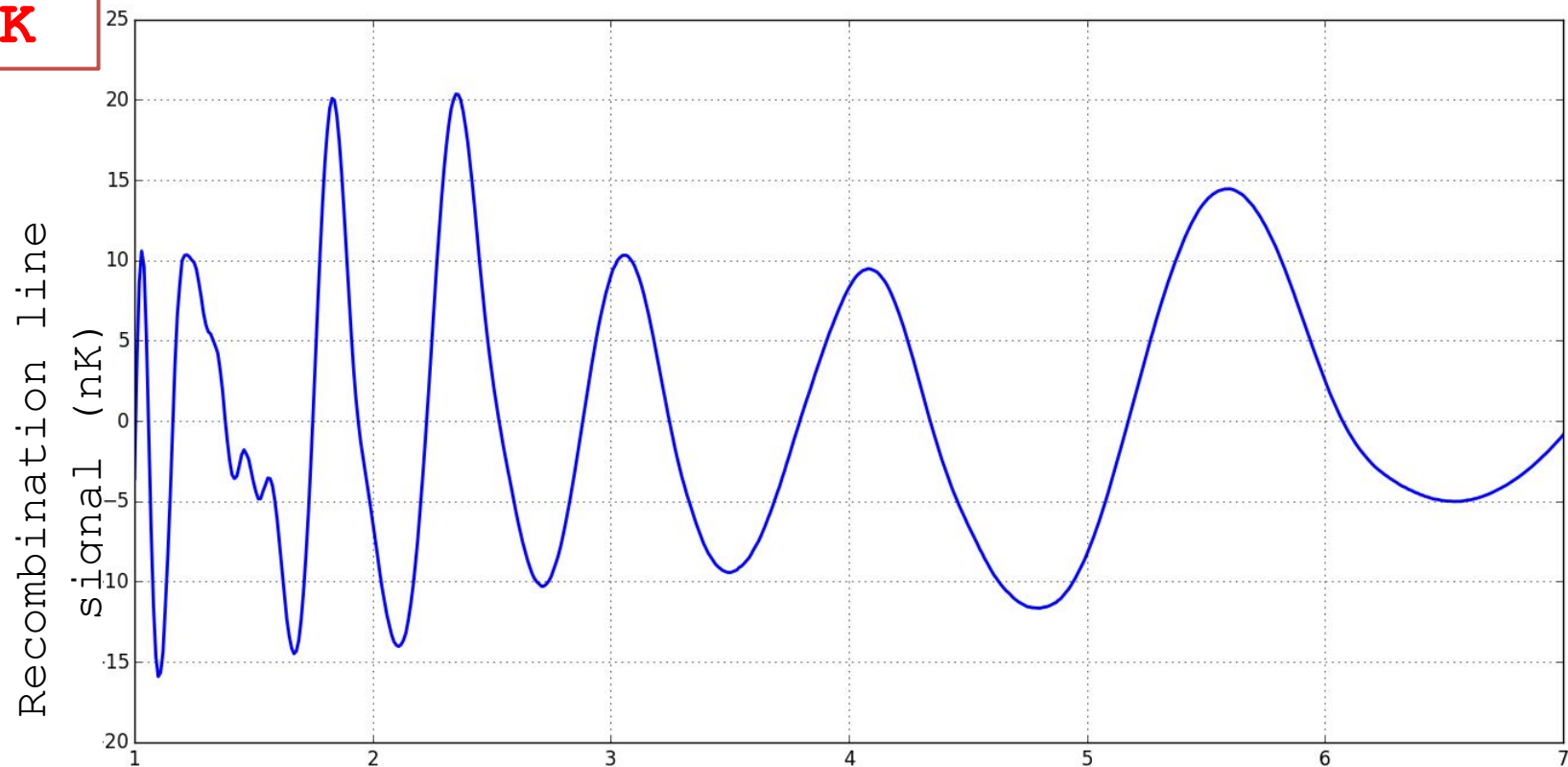


(Chluba & Ali-Haïmoud, 2016)



Additive spectral structure expected in nano Kelvin units owing to cosmological recombination of hydrogen and helium in the 1.5 - 7 GHz range. Enclosed is the APSERA observation band.

$\sim nK$



Baseline subtracted signal derived from CosmoSpec

$\sim nK$ 

Baseline subtracted signal derived from CosmoSpec

Symbolic Regression

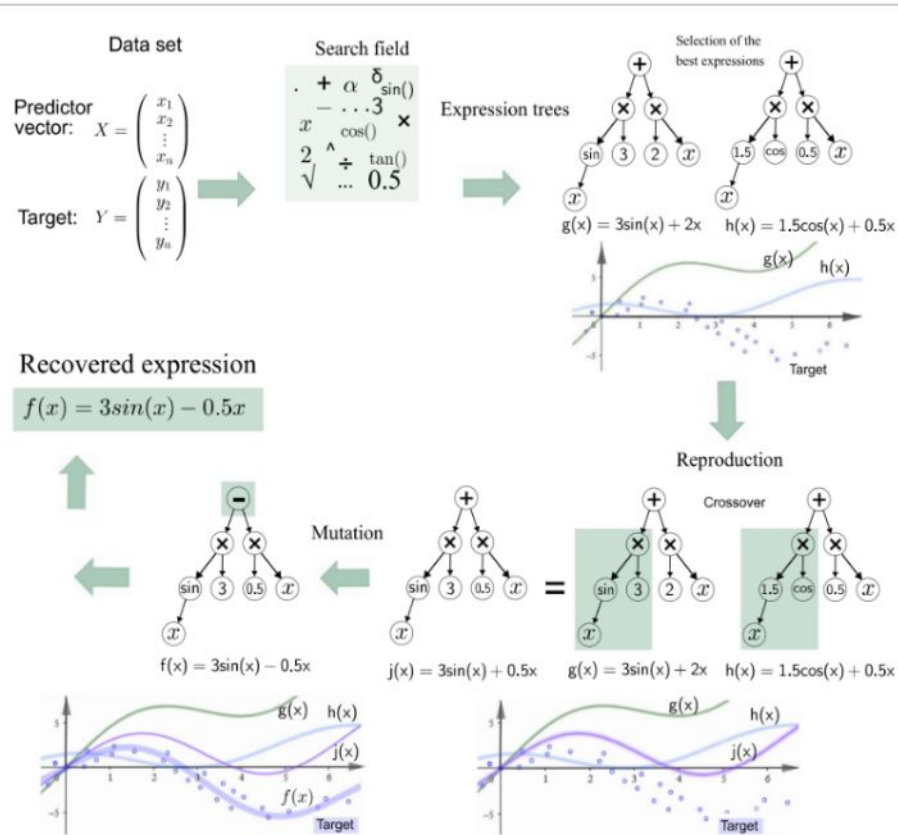
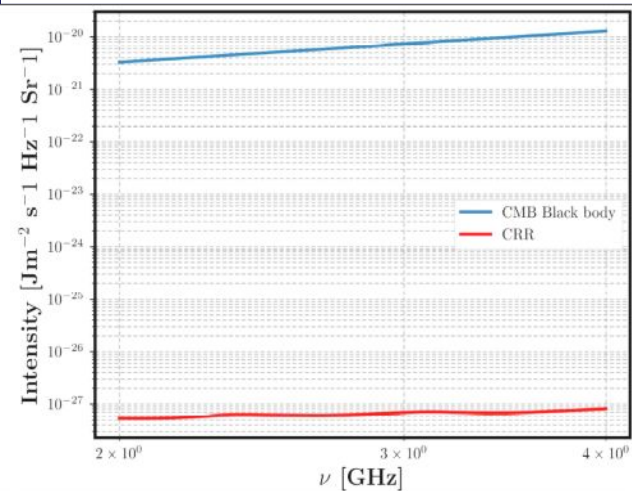


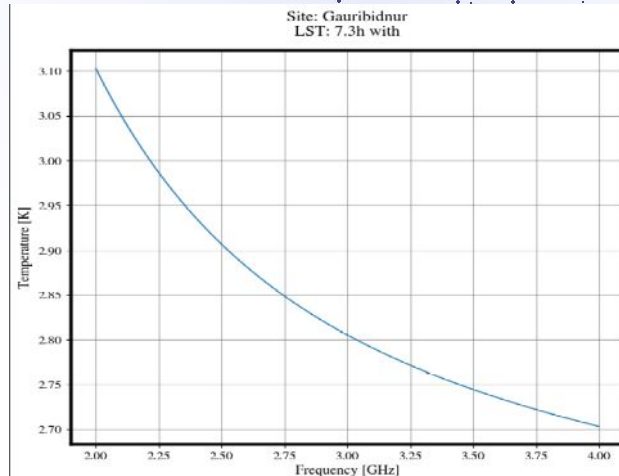
Figure 1. Diagram of the usual process for adjusting a genetic programming-based symbolic regression algorithm. Each method iterates new combinations of functions, tuning model complexity until the best fit is found.

- An interpretable closed-form expression you can read, differentiate, and reason about.
- Extrapolation: $F = G \cdot m_1 m_2 / r^2$ keeps working outside the training range; a spline returns nonsense the moment you leave the knots.
- Compactness: a few dozen characters instead of thousands of coefficients.
- Discovery: SR can recover a physical law or reveal that a variable is irrelevant, because the structure is itself the output.
- Deployability: the expression drops into a spreadsheet, firmware, or a textbook.
- Best suited to low dimensional problems where user believes compact law exists, where "the model is a formula" is a requirement.
- We use pySR built on Julia and interfaced by Python, using regularised evolution, simulated annealing, and gradient-free optimisation.

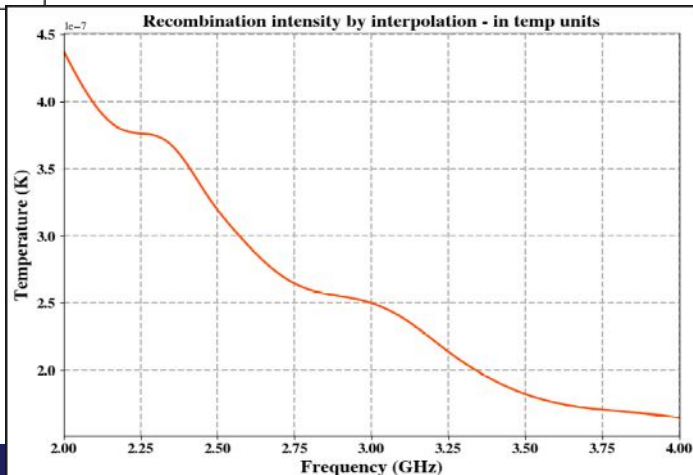
The CRR Problem



The Cosmic
Recombination
Radiation(CRR) is 7-orders
less than Cosmic
Microwave
Background(CMB)



The CRR spectral ripple
across 2-4GHz



A spectra generated with
CRR buried in it with LST
correction at a location
between 2-4GHz



Curve fit
adjusted
parameters

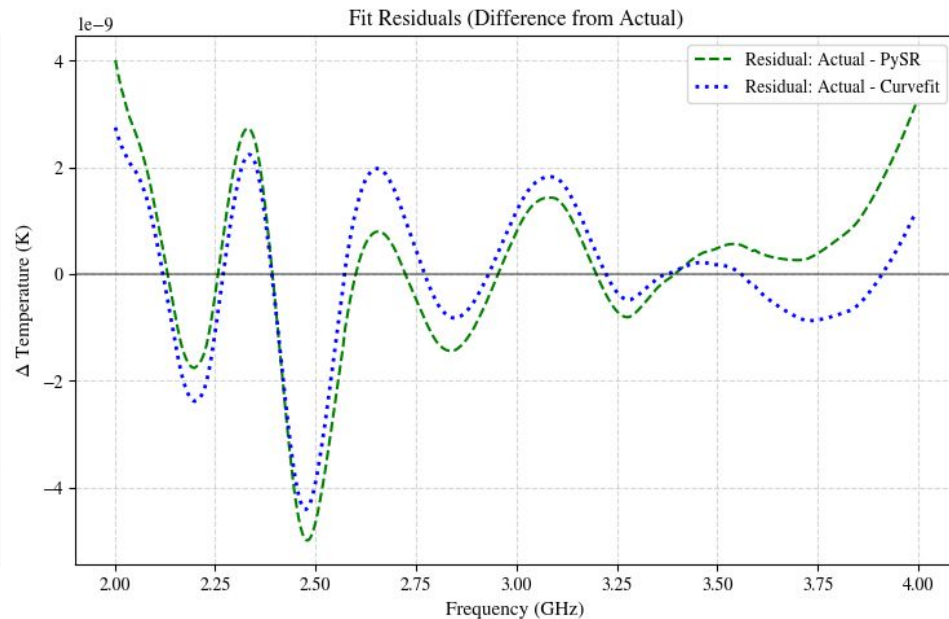
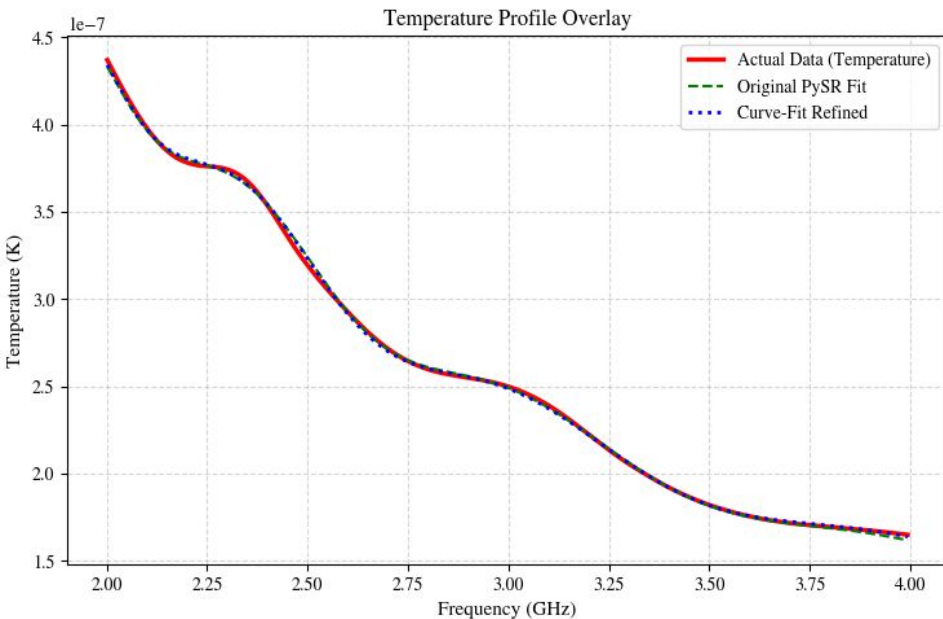


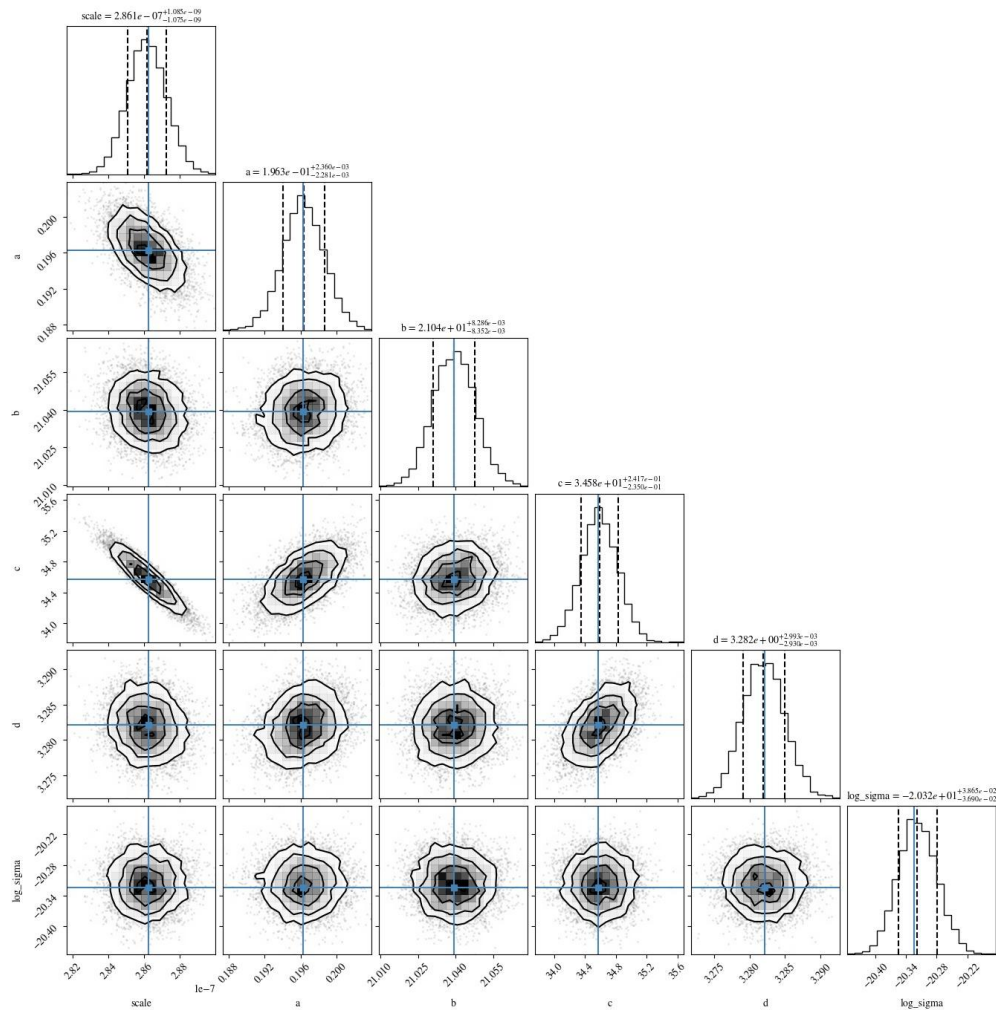
```
Scale: 2.862369e-07 ± 1.110511e-09  
a: 1.962597e-01 ± 2.383741e-03  
b: 2.103944e+01 ± 8.379437e-03  
c: 3.457182e+01 ± 2.443076e-01  
d: 3.282099e+00 ± 2.976455e-03
```

final
statistical
values



```
Reduced Chi-squared ( $\chi^2_\nu$ ): 1.0140  
R2 Value: 0.999668  
Chi-squared ( $\chi^2$ ): 361.0003  
Degrees of Freedom ( $\nu$ ): 356  
p-value: 0.416255
```

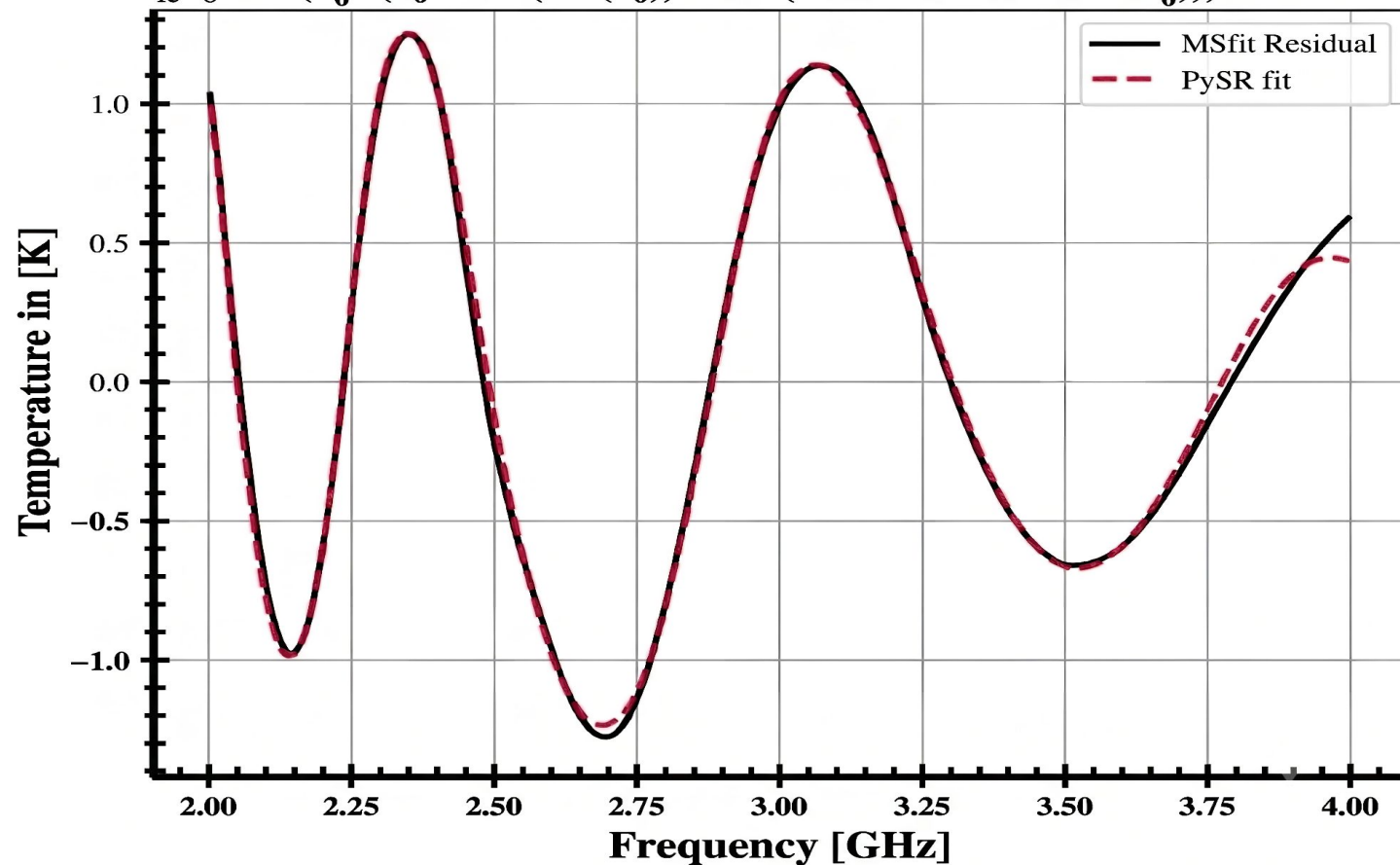




- Using a 5 term parameterization we are now able to analytically describe the CRR signal.
- We are now equipped with the right framework for joint modeling with foregrounds, and hence signal inference for detection.
- Next step – see if the model can have a physical interpretation of the signal, and evaluate how this model / parameterization behaves when moving beyond detection to “measurement” regime of signal – and sensitivity to Y_p , T_{cmb} , etc.

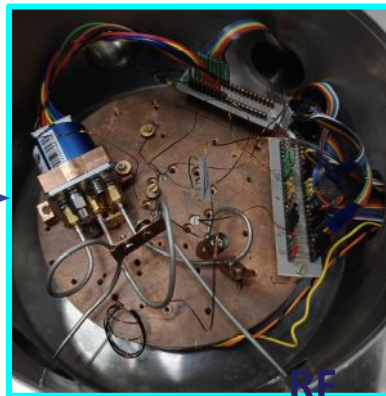
PySR equation:

$$f(x_0) = -2.955437\text{e-}9 \cdot \exp(\log(x_0) \cdot \cos(0.98301125 \cdot x_0^2)) + 2.955437\text{e-}9 \cdot \log(x_0) \\ + 1.7782729\text{e-}6 \cdot (\sin(1.4853761 \cdot x_0^2) + 0.030599415) \cdot \cos(2.1137702 \cdot x_0) \\ + 1\text{e-}8 \cdot (x_0^4 \cdot (x_0 + \sin(\cos(x_0))) - \cos(1.21531875258711 \cdot x_0^2)))$$





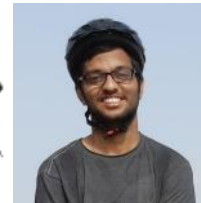
Antenna



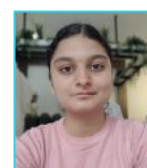
RF



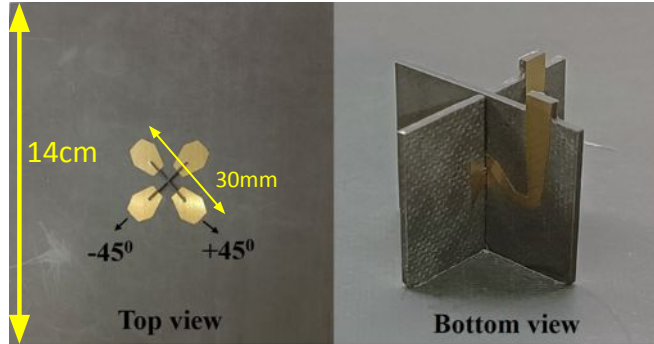
APSErA Prototype (Gen1 RFSoc)



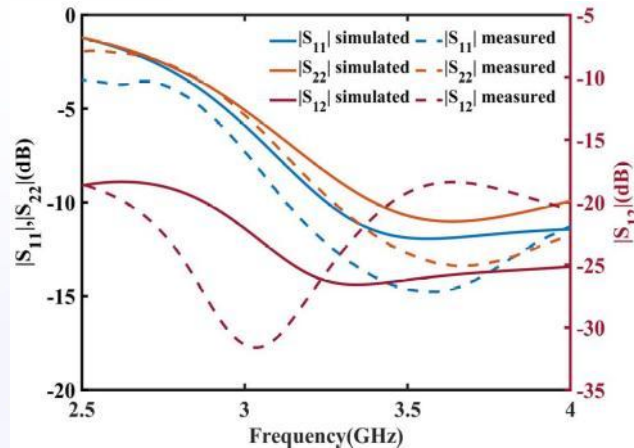
Cryogenics



VERSION 1 - FANTAIL SHAPED DIPOLE ANTENNA

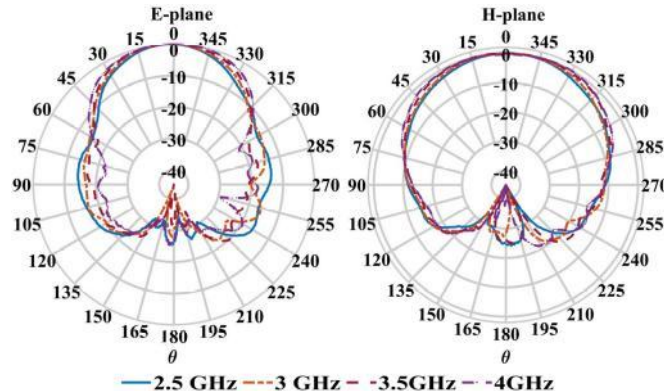


Keerthipriya Sathish et al, Antenna Design, 2024 Astronomical Journal, 168 39



THIS DESIGN IS SO FAR THE STATE OF THE ART

- The antenna has 6% 3dB beamwidth dispersion.
- The antenna gain without reflection efficiency is around 8 – 9dBi within the band.
- The antenna residues are at least 10 times smaller than the other antennas in Literature



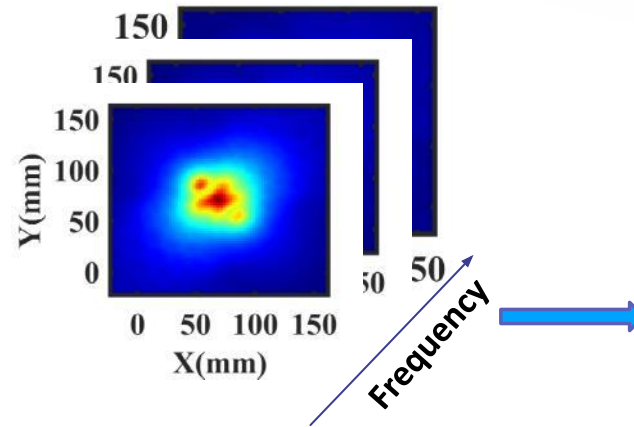
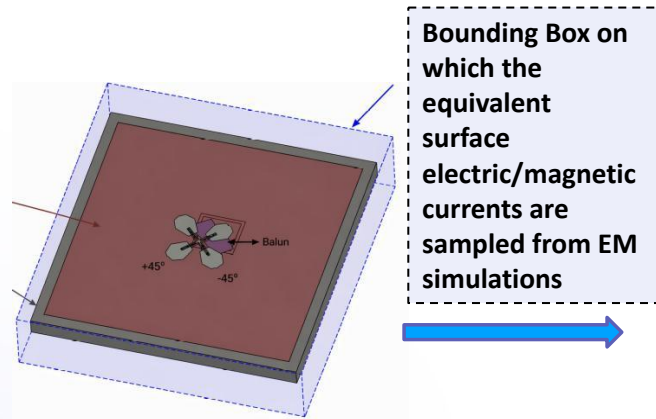
Beamwidth: 55° (E-plane) , 75° (H-plane)

Challenges

1. In EM simulation tools just by blind optimisation, it is difficult to further improve this performance
2. Calculating residues for every design change would be required which is time consuming
3. $|S_{11}|$ has to be maintained in same shape without resonances which is also difficult.
4. It becomes like a multiparameter optimisation

GOAL

Instead of heuristic tuning, what if we could directly pinpoint *where* on the antenna, and at *which frequencies*, beam chromaticity originates, and design with that insight?

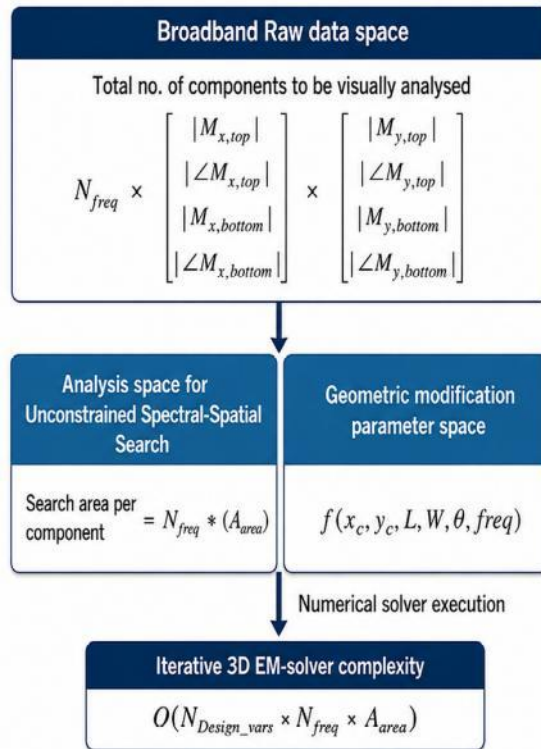


This is further fed to the Machine learning pipeline

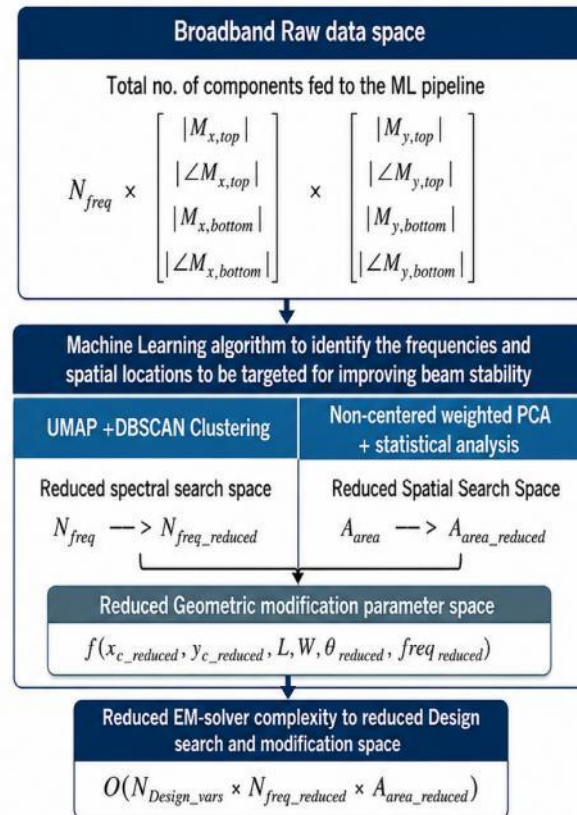


MACHINE LEARNING PIPELINE

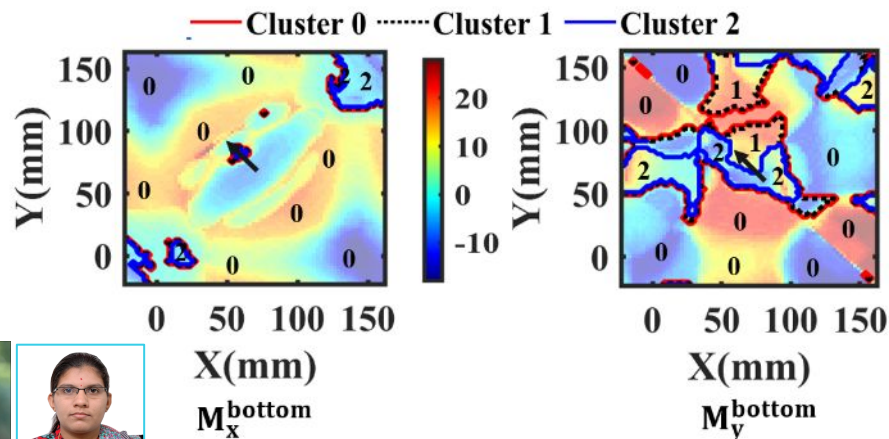
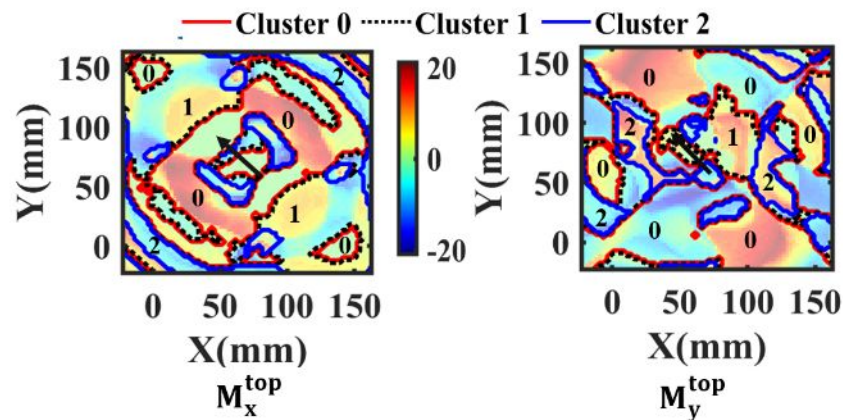
Traditional Workflow without using ML



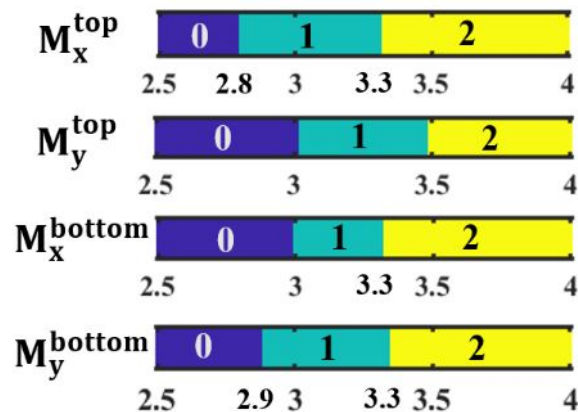
Proposed Workflow using unsupervised ML



Top plane



Bottom plane



Cluster Frequencies



IMPROVED ANTENNA DESIGN

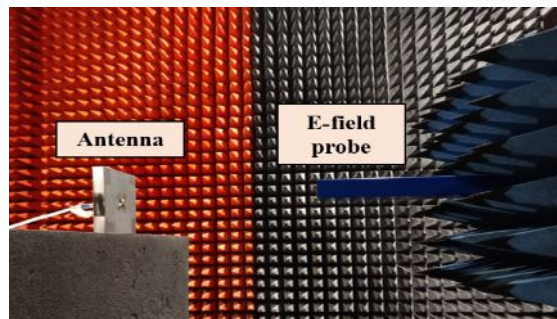
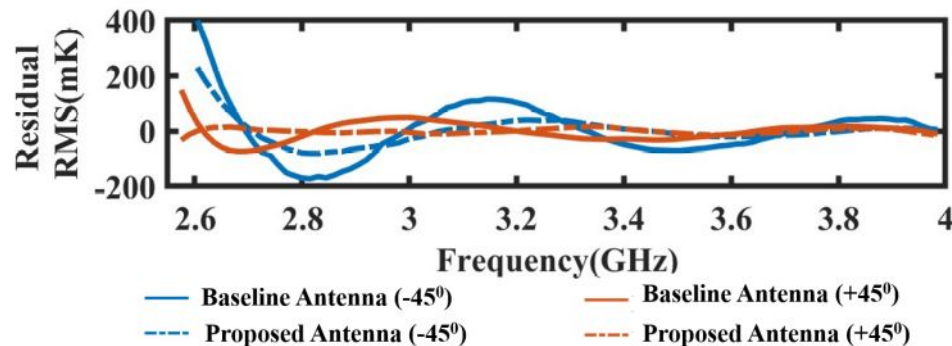


Top View



Bottom View

Fabricated antenna

Pattern measurement in
Near Field Chamber

HIGHLIGHTS

1. The number of clusters have reduced to **2**
2. The beam stability in this design improved to **+/-3.5°**
3. This antenna RMS sensitivity: **40mK, 15mK** which is 50% improvement compared to the baseline

RFI SURVEY SETUP IN VARIOUS LOCATIONS

Setup in Gauribidanur Observatory



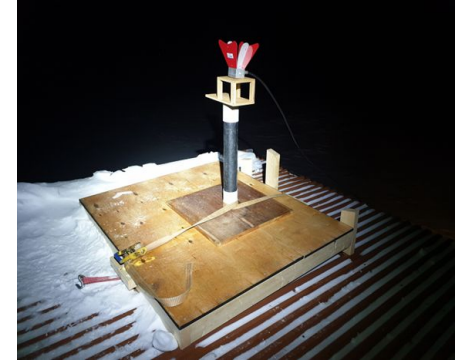
Setup in Hanle Observatory



Setup in Thamchung giri



Setup in Himadri Arctic station

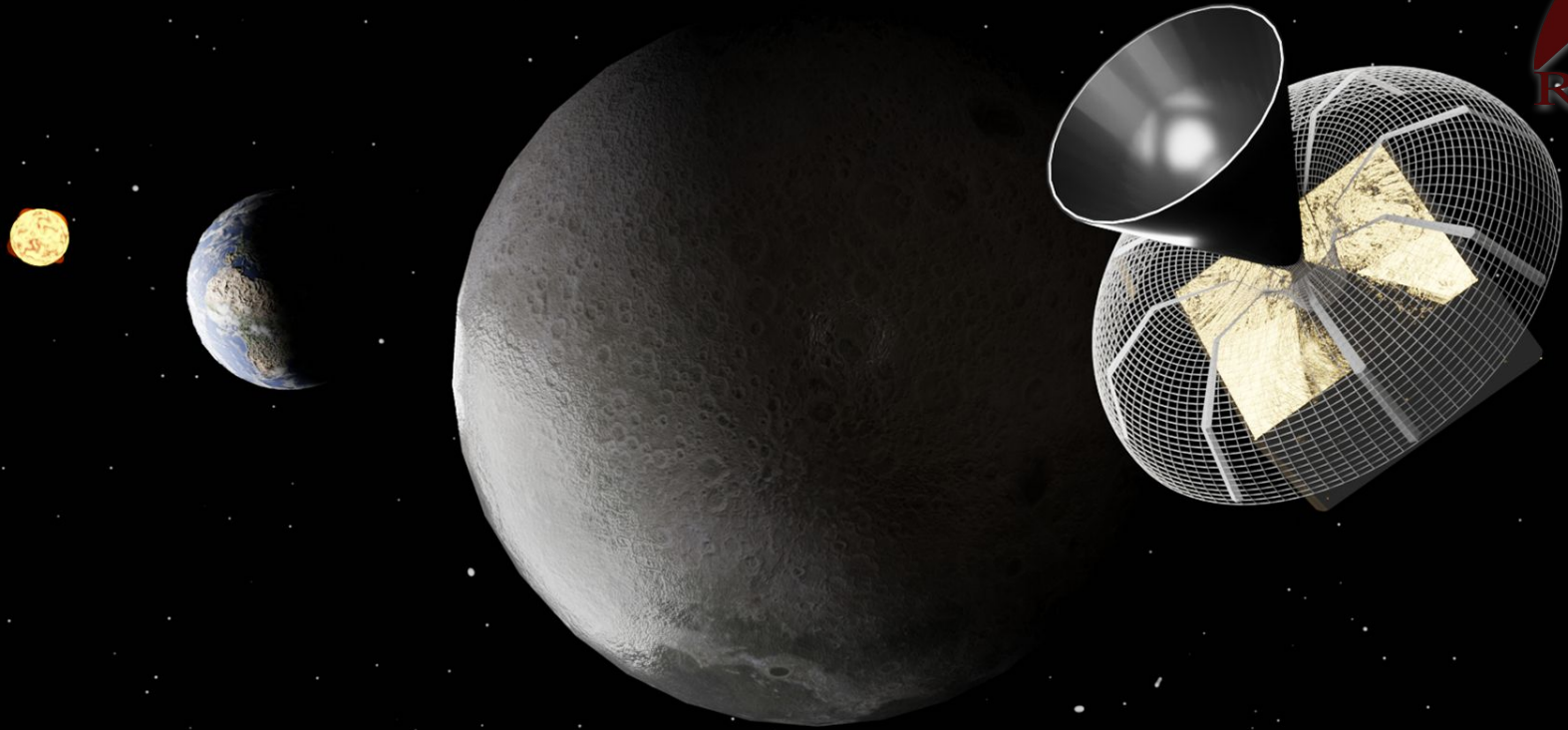


Picture credit: B.S. Girish, RRI

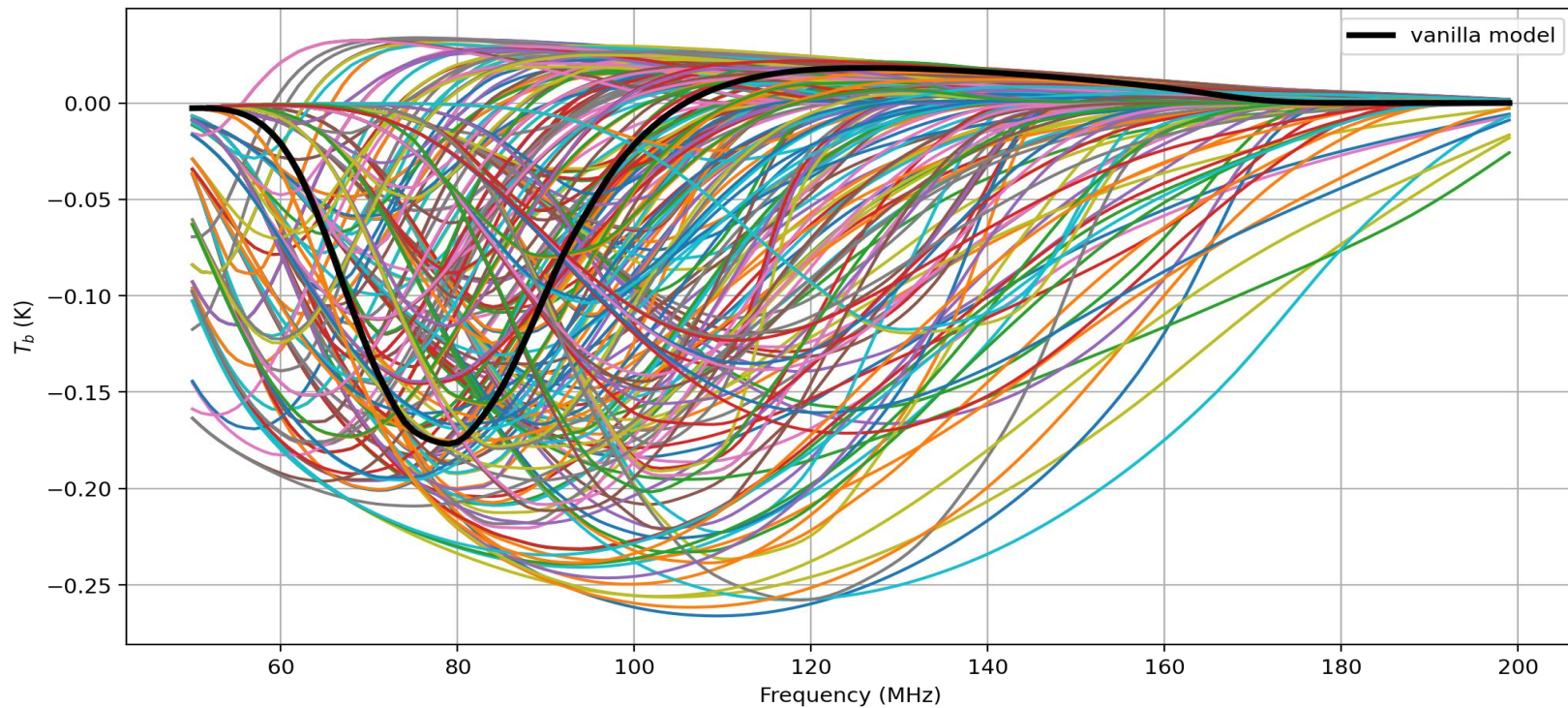
Shielding cage to enclose the Laptop, Spectrum analyzer and the receiver



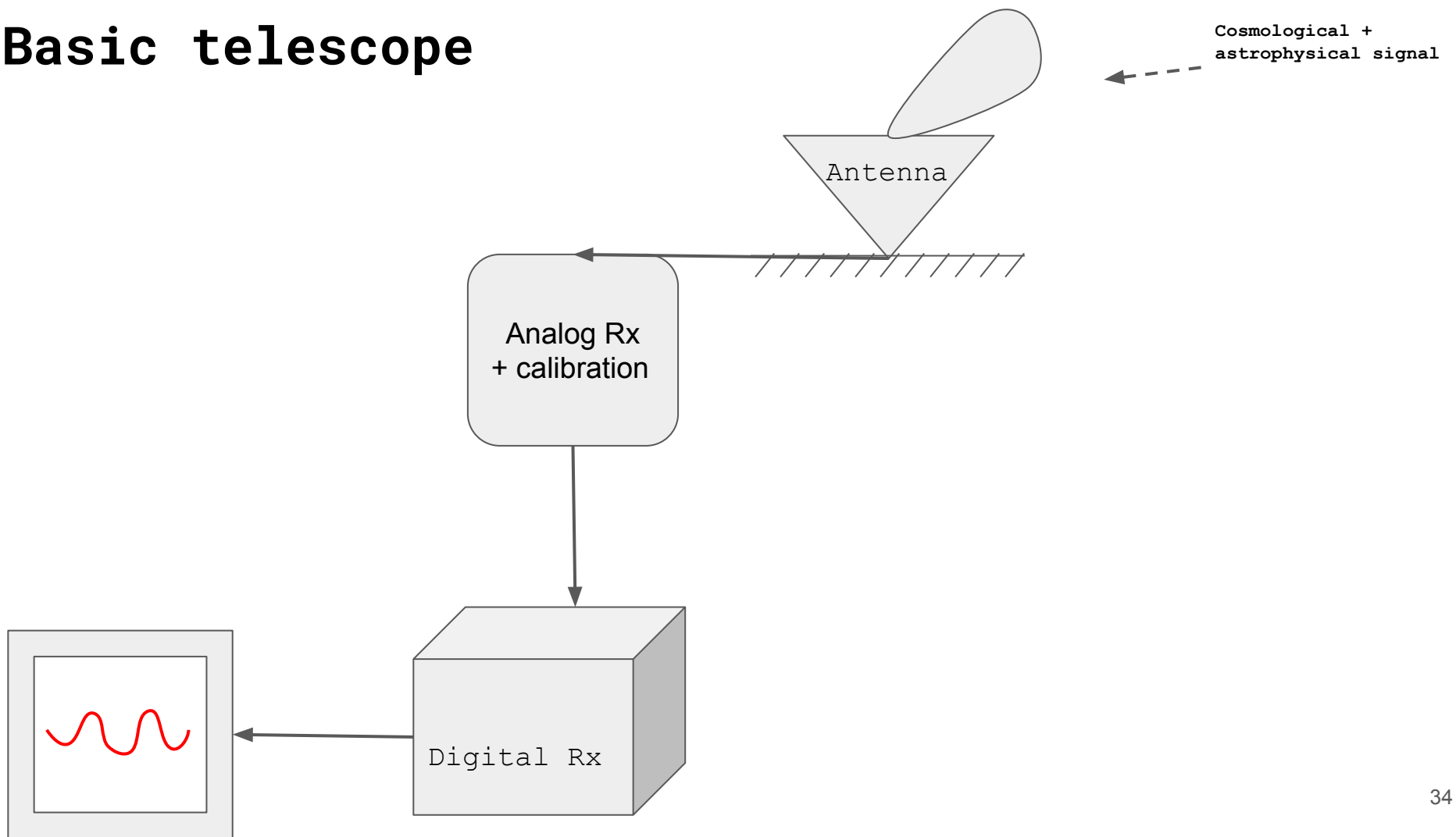
Observations were carried out during day and night each for 3 hours duration



Cosmic Dawn

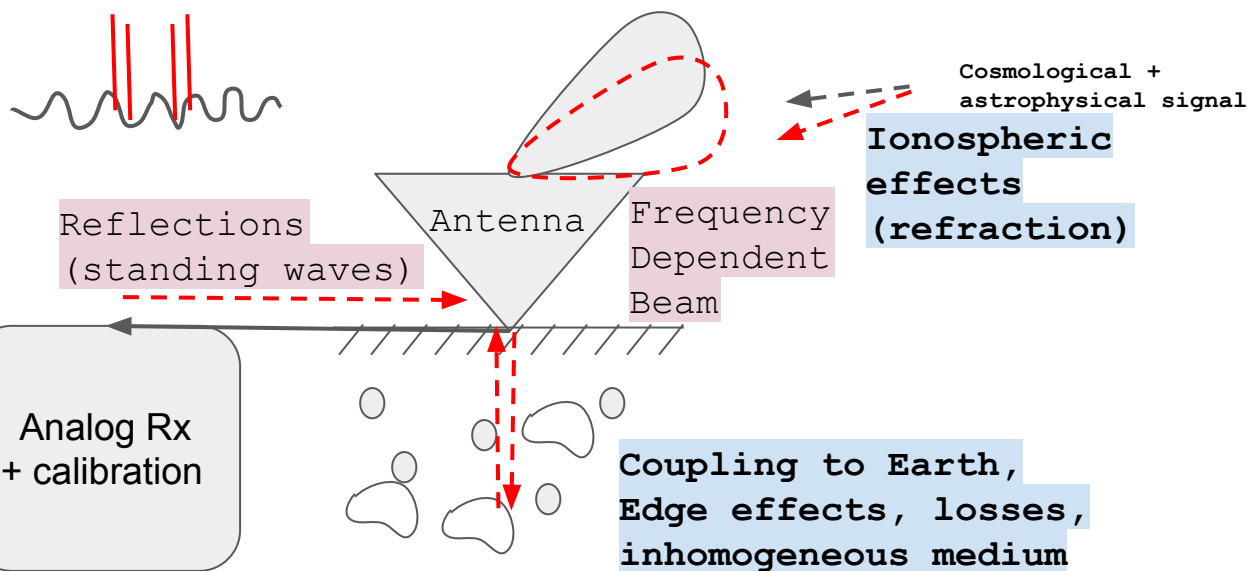


Basic telescope



IN PRACTISE

Radio
Frequency
Interference
(RFI)



Data-analysis
methods

Self generated
RFI

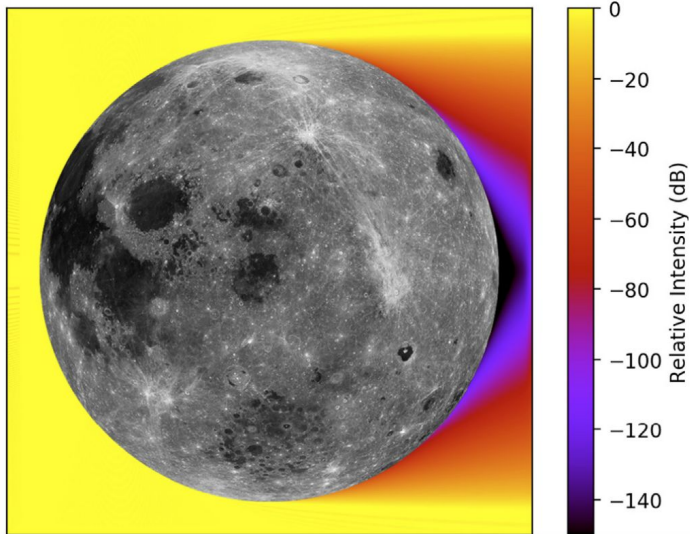
Dynamic Range
limitations

Minimized in free
space over lunar
farside

Needs to be a part
of experiment design

Why Lunar Farside?

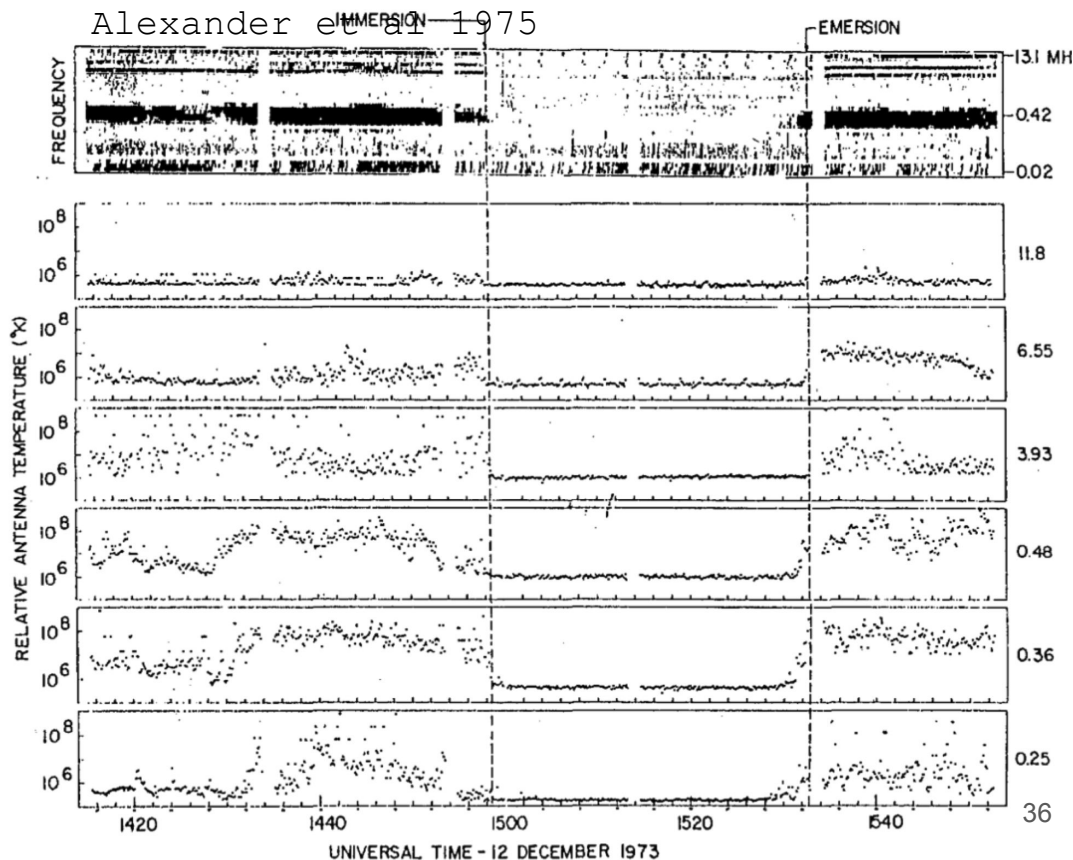
Bassett et al (2020)



The moon is an attenuator.
Farside of the moon attenuates
terrestrial RFI.
It provides a 'clean' environment.

RAE-2 measurement : 25 kHz - 13.1
MHz

Alexander et al 1975



WHAT IS PRATUSH?

प्रत्यूष



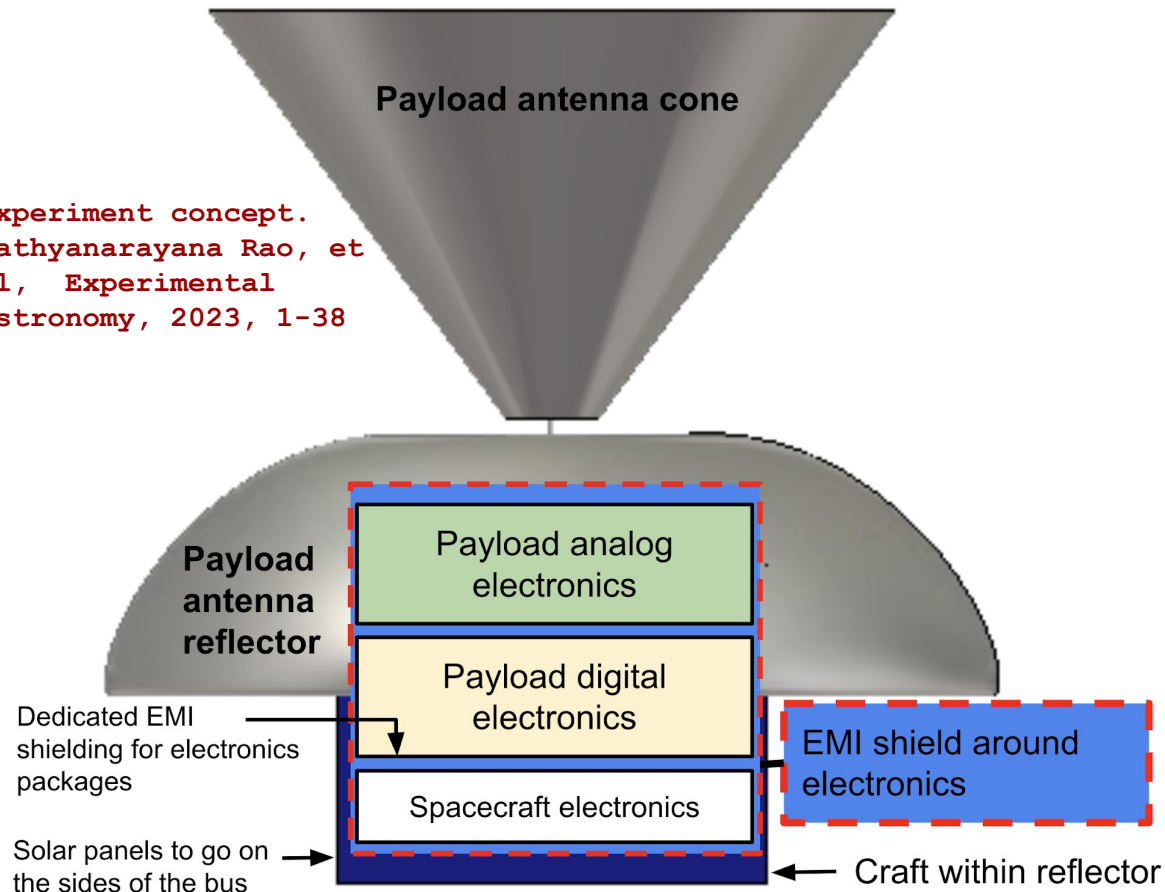
Dawn, Sun

- ★ **PRATUSH: Probing ReionizATIOn of the Universe using Signal from Hydrogen**
 - 40 - 200 MHz (CD and EoR)
 - Baseline design 55 - 110 MHz (CD)
 - Lunar orbiter custom designed for the primary science goal of detecting the signal from CD/EoR
- ★ **Ground-based counterpart experiment SARAS(1,2,3) at Raman Research Institute**
- ★ **Funded for pre-project studies by the Indian Space Research Organisation (ISRO) since 2019**
- ★ **Laboratory model is ready - undergoing subsystem testing. Will be followed by system level testing.**
- ★ **Expected to fly as a dedicated craft**
- ★ **Expected to fly in 2 phases : Phase I as an Earth Orbiter and Phase II as a Lunar Orbiter**



Baseline Design (55 - 110 MHz)

Experiment concept.
Sathyanarayana Rao, et
al, Experimental
Astronomy, 2023, 1-38

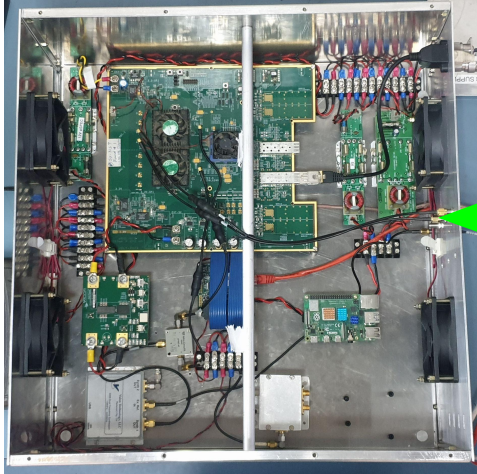


BLOCK DIAGRAM AND CONCEPT MODEL HARDWARE

Analog receiver modules using commercial components in chassis



Integrated digital receiver using COTS / in-house development in chassis



Antenna

Monocone antenna design on shaped reflector (55 -110 MHz)



Analog Receiver + Calibration

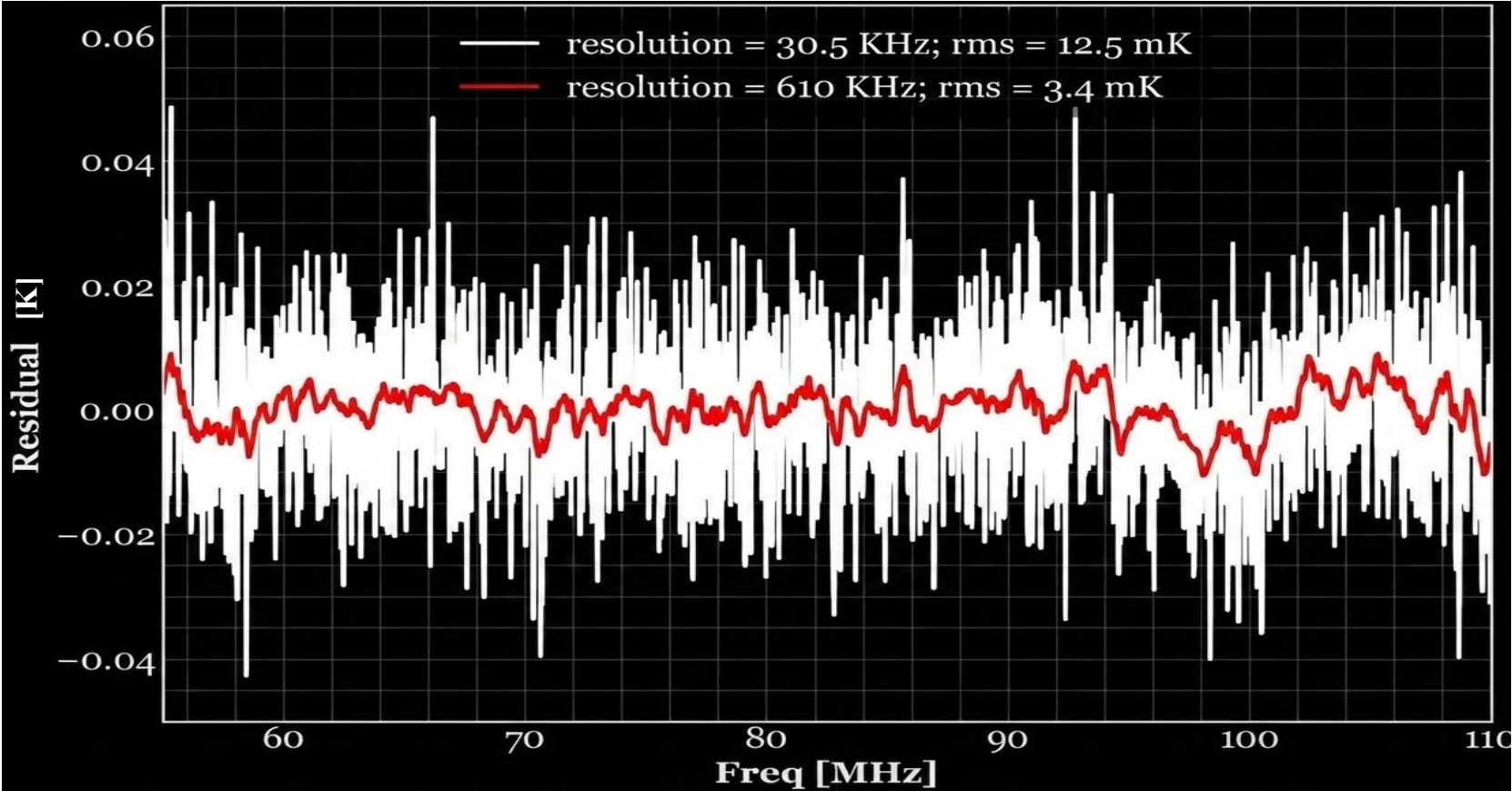
Digital receiver

Satellite / bus

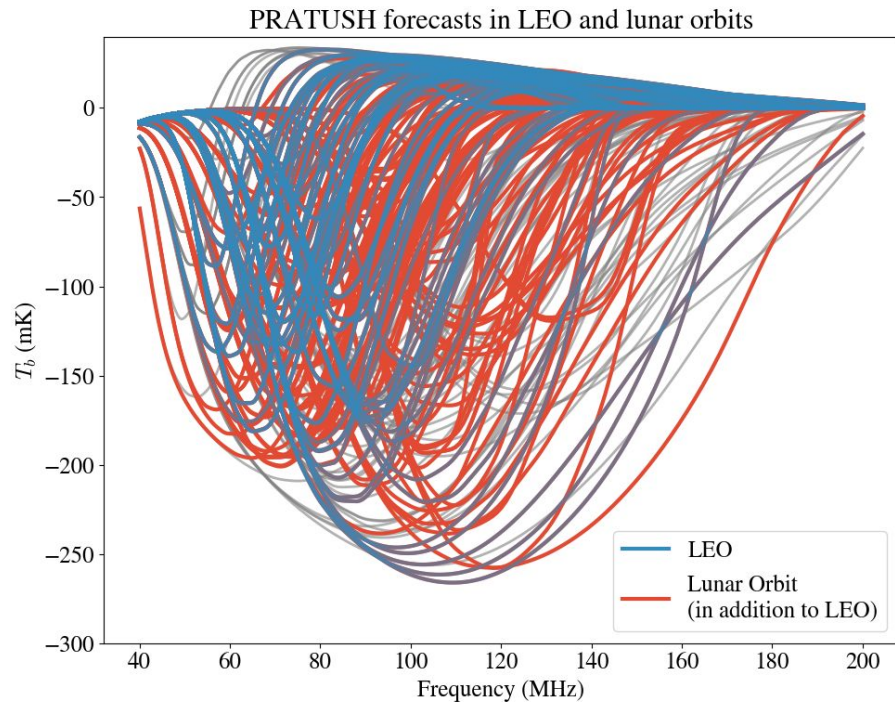
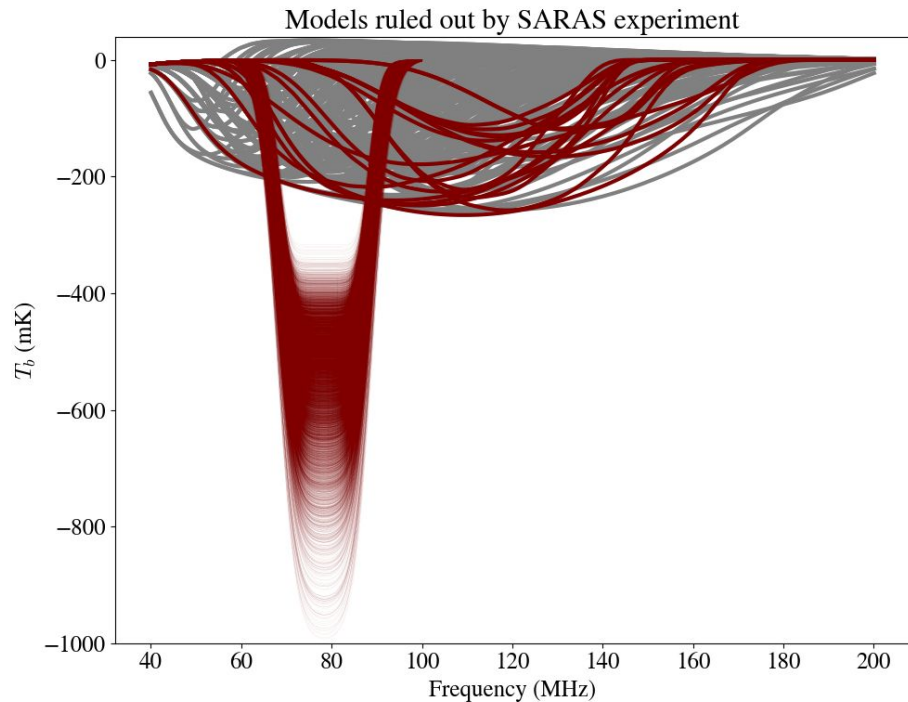
Assumed 2x12 U cubesat bus



Laboratory Model of PRATUSH has sensitivity to detect the 21-cm signal



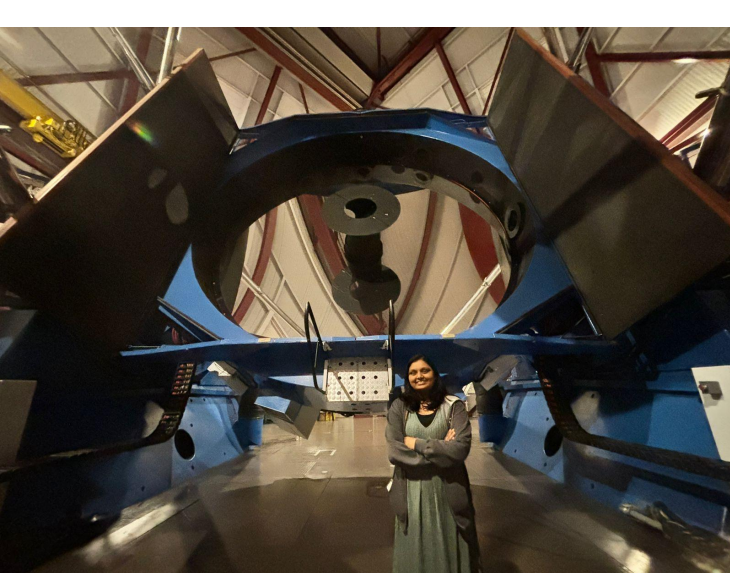
Ground based vs LEO vs Lunar



Summary

- There is rich information in global cosmological signals
- Signals from the epoch of recombination trace time dependent additive distortions in the CMB spectrum, at 1 part per billion - rich in thermal and ionization history
- Signals from Dark ages, cosmic dawn, epoch of reionization contain information about one of the big missing pieces in cosmology - baryonic evolution and primordial star / galaxy formation
- Astrophysical foregrounds have different spectral structure compared to the cosmological signals - can be used for signal detection algorithms
- Instrument related artefacts, and environmental artefacts quickly become the limiting factor in signal detection - custom precision radiometer design with specific attention to calibration
- Lots of scope for discovery - about foregrounds, ionosphere, cosmology and cutting edge technological developments

THANK YOU. QUESTIONS?



What we do!

